AFIT/GEP/ENP/92D-5

THE EFFECT OF OXIDE LAYERS AND BORON DOPING ON THE BREAKDOWN OF HIGH PURITY SILICON

THESIS

Brian A. Hibbeln, Second Lieutenant, USAF

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THESIS

Presented to the Faculty of the School of Engineering
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Master of Science in Engineering Physics

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Preface

The purpose of this experiment was to determine the effect of oxides and boron doping on the breakdown characteristics of high purity silicon. This information is needed to help determine mechanisms that will inhibit electrical breakdown in silicon, enabling the development of a Photoconductive Semiconductor Switch (PCSS). A solid state PCSS would be smaller, more reliable, have a longer lifetime, and weigh less than the gaseous discharge switches that are currently used for pulsed high voltage, high current applications.

It was found that by placing a thin oxide layer near the anode, that the breakdown potential of silicon increased from 16 kV/cm to 37 kV/cm. In this configuration, an excellent PCSS was also demonstrated. When an Nd:YAG laser of 2 mJ was used to illuminate the sample prior to the application of a voltage pulse, the effective impedance of the sample was reduced by three orders of magnitude.

In performing this experiment and writing this thesis I have many people to thank. First of all, I would like to thank my faculty advisor, Dr. William Bailey. I thank him for always being available for assistance and helping me to develop a greater understanding of the "physics" involved. I am also deeply indebted to Dr. Bish Ganguly, my laboratory advisor. His patience in explanations and assistance in the lab helped me to get "good data" along with knowledgeable advice. I also wish to thank Dr. Alan Garscadden who provided me with an excellent working environment as well as motivation to continue my work. A word of thanks is also owed to Dr. Bletzinger, Doug Abner, and Bob Knight for providing assistance in my many times of need. Finally, I wish to thank my family, friends, and next-door neighbors for tolerating and supporting me during the course of this work.

Brian A. Hibbeln

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Abstract

For many applications such as lasers and radar drive circuits, there exists a need for solid state high voltage, high current switches. Current gaseous discharge switches fail to satisfy the ruggedness, reliability, and lifetime requirements of today's systems. A promising alternative is the Photoconductive Semiconductor Switch (PCSS). The limiting factor in the operation of these switches is the occurrence of breakdown through channels formed slightly below the surface. A theory on the formation of these channels is presented based upon band bending at the metal-semiconductor interface, a nonhomogeneous space charge due to irregular trap distributions, and thermal runaway in localized regions. Experimental results on the effect of thin oxide layers and boron doping at the metal-semiconductor junctions reveal that the junctions play a very important role in the breakdown of the samples, changing the breakdown potential by almost a factor of three. By placing a thin oxide layer at the anode face of a sample, an excellent photoconductive switch can be produced. The resistance of this switch was changed by three orders of magnitude through optical illumination.

Introduction and Background

For many applications such as lasers and radar drive circuits there exists a need for pulsed, high voltage, high current switches. Currently, gaseous discharge switches such as thyratrons, krytrons, ignitrons, and spark gaps are used in these applications. These types of switches exhibit many undesirable characteristics such as poor reliability, low current densities, and short lifetimes.(1) It would be advantageous to replace these with a solid state semiconductor switch, the most promising of which appears to be the Photoconductive Semiconductor Switch (PCSS).(2) A PCSS is typically made from a high resistivity (intrinsic) semiconductor, such as silicon or GaAs, whose conductivity increases by four or five orders of magnitude upon optical illumination. Silicon PCSS's have been used to switch large energy pulses of short duration with high repetition rates and precise timing control. These attributes combined with its high voltage and current ratings, and long life expectancy, make a silicon PCSS an excellent candidate to replace current gaseous discharge switches.(1)

At this time, the limiting factor in the operation of these switches is the occurrence of breakdown at or slightly below, the surface of the semiconductor. This problem has hampered the development of high voltage semiconductor devices for the last 30 years. These dielectric breakdown phenomena can destroy the semiconductor or create a permanent, highly conductive path between the electrodes.(2) Although the bulk breakdown of silicon is quite high (200 kV/cm), flashover at the surface can occur with fields on the order of only 20 kV/cm.(3) Until recently, the flashover phenomena in semiconductors was modeled as an insulator breakdown. Insulators have a high secondary electron emission coefficient which leads to a breakdown on the surface of the insulator. Recent experiments have shown that a simple surface breakdown is clearly not what is occurring in the case of silicon.(3) Although many of the physical mechanisms

of this flashover are not completely understood, a variety of attempts have been made to limit its occurrence.

In the early development of high-voltage (>100 Volts), bipolar diodes and transistors it was found that surface breakdown occurred quicker than the bulk avalanche multiplication inside the semiconductor.(3) This early problem was overcome by simply beveling the edges of the device. This technique decreased the sharp edges of the device and thus decreased the electric field in this region. By using very acute beveled edges, these early low power devices were then limited by the slower, bulk avalanche breakdown. Todays devices must be able to switch tens of kilovolts and simply beveling the edges is not sufficient.

More recently, Loubriel, O'Mallay and Zutavern have been able to achieve fields as high as 91 kV/cm simply by immersing the silicon sample in pure, cooled water.(4) Although this result is not fully understood, it is believed that the high dielectric constant of water (80) forces the high field at the metal-dielectric-semiconductor interface (the triple point) to exist further inside of the silicon (dielectric constant of 11.8). Gas dielectrics on the other hand, have a very low dielectric constant thus allowing high fields to exist at the surface of the semiconductor where flashover is likely to occur. Similar results have been reported by Pocha, where electric fields of up to 100 kV/cm have been achieved by immersing the samples in high pressure SF_6.(5) Although the addition of water or SF_6 tends to increase the breakdown potential, neither are very practical from a device standpoint.

A more practical mechanism reported by Loubriel, has been the metallization of the contacts used to apply the field across the sample. By depositing a thin layer of gold to both ends of the sample, the pitting that was usually noticed at the triple point was almost non-existent. This metallization achieved a reduction in the pitting even when a

gas dielectric was used. It is believed that metallization leads to a more diffuse injection of charge and thus reduces the pitting.

An interesting result related to the alteration of interface properties was also reported by Peterkin and Williams.(6) They found that by illuminating a small region of the sample near the cathode with a 100 uJ laser pulse of 532 nm, they were able to completely inhibit the flashover of a 30 kV, 250 ns pulse over a 10 mm region. They also suggested that the inhibition of flashover might be duplicated by p-doping a small region near the cathode. It was hoped that this doped region would provide recombination centers for the 'hottest' electrons and help to distribute the current on the semiconductor side, much like metallization does on the metal side of the interface. The combined effect of these two processes would then cause a net reduction of the electric field at the metal-semiconductor interface and thus help to inhibit the onset of flashover in this high-field region.

In this paper, the effects of doping the metal-semiconductor junction with boron and oxide are reported. The breakdown characteristics of three different silicon samples were studied: a pure sample, a sample with boron doping at one end, and a sample with an oxide layer at one end. All the samples were metallized at both ends to facilitate injection and distribute the charge across the metal-semiconductor interface without causing damage or pitting to the sample. The boron and oxide ends of the samples were tested at both the cathode and the anode to evaluate the orientation dependence of the breakdown potential. The I-V curves of the samples in all configurations were then examined to determine the various breakdown mechanisms involved.

Theory

Insulator Breakdown

Our understanding of semiconductor breakdown was initially guided by the theories of insulator breakdown. There are two major theories of insulator breakdown, that of Anderson and Brainard (7), and that of Miller (8).

Anderson and Brainard propose that a secondary electron emission avalanche is initiated by a field emission at the cathode. These electrons then impact the surface of the insulator causing secondary electron emission due to the high secondary electron emission coefficient of insulators. This cascading of electrons down the surface of the insulator leaves a net positive charge, which further enhances the field emission from the triple point. These cascading electrons then ionize the normally desorbed gas from the sample through electron impact ionization, forming a plasma just beyond the surface of the insulator. It is believed that the flashover current initiates through this resulting plasma.

Another theory on insulator breakdown is presented by Miller.(8) He proposes that the initial electrons are released through field emission directly at the triple point (the point where the metal, semiconductor, and ambient meet), instead of at the cathode where Anderson and Brainard have suggested. This source of field emission then provides the electrons that avalanche, through secondary electron emission, across the surface of the insulator and eventually lead to breakdown. It is important to note that insulator breakdown involves large amounts of current moving across the surface of the insulator and thus usually has large amounts of visible emission or 'arcing' present in these regions. This large visible emission is not present in semiconductor breakdown experiments.

Semiconductor Breakdown

Recent experiments with silicon have shown that in many cases, breakdown currents of several tens of amps have been recorded with no visible emission being observed. Furthermore, it was not until currents of 300 amps were observed that a visible emission was present between the cathode and the anode.(9) It was then clear that the breakdown current must be flowing somewhere inside the semiconductor. Further studies with Scanning Electron Microscope (S.E.M.) photomicrographs have revealed the formation of narrow current channels just beneath the surface of the semiconductor. It is through these channels or filaments that the majority of the breakdown current must flow.

The process by which these channels form is not completely understood. This paper offers an explanation derived from a combination of the early work of Garrett and Brattan with space charge (10), the classical band theory of semiconductors (11), and the idea of thermal runaway (3).

Channel Formation and Current Filamentation

Our model of surface flashover proposes that the breakdown occurs due to the space charge at the interface of the metal-semiconductor junction. This space charge is greatly increased by the presence of an oxide layer or traps at the interface. This is shown schematically in Figure 1.

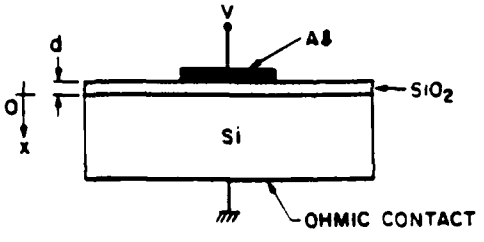


Figure 1: A Silicon Sample with an Oxide Layer

When a metal and semiconductor are brought into intimate contact, the bands of the semiconductor bend to match up the Fermi levels of the two materials. It is this bending of the bands that sets up an accumulation or depletion region on the semiconductor side of the interface, thus giving rise to an initial space charge region. Figure 2 depicts two of the possibilities when a metal-oxide-semiconductor interface is biased both positively and negatively.(11)

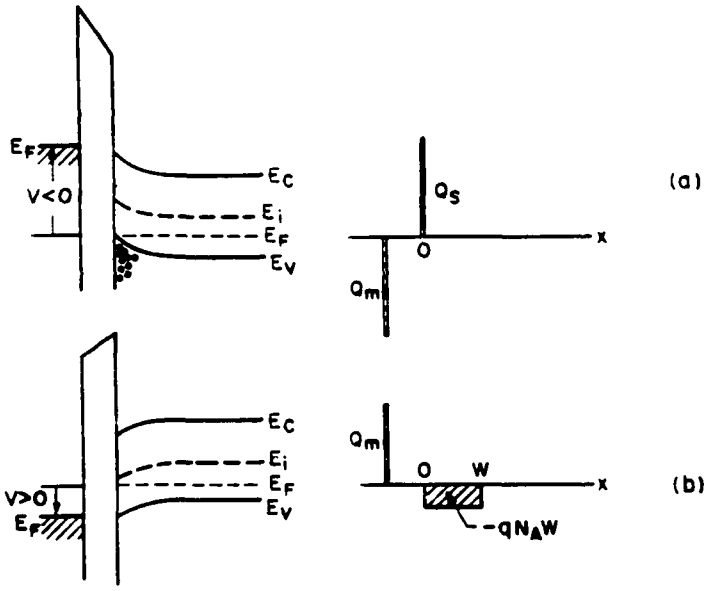


Figure 2: Energy Bands at a Metal-Oxide-Semiconductor Interface

In Figure 2a, a negative bias has been applied to the metal contact and the bands of the semiconductor have been forced to bend upward. This causes an accumulation of holes at the oxide-semiconductor interface and a space charge results. The corresponding charge distribution is shown to the right, where (Qm) is the charge on the metal side of the interface and (Qs) is the charge on the semiconductor side of the interface. In Figure 2b, a positive bias has been applied to the metal contact now forcing the bands of the semiconductor to bend downward in order to match the Fermi levels. This is known as

the depletion case and a larger space charge region is built up due to the higher mobility of the electrons. In this figure, (w) is the width of the space charge region and (-q Na w) is the total charge of this region, where (q) is the charge on the acceptors and (Na) is the number density of the acceptors. It is important to note that in both of these cases the electric field formed by the space charge tends to enhance the longitudinal field at the interface region.

It is this enhancement of the field at the interface region that Garrett and Brattain propose leads to the initial injection of high velocity electrons. The channels are then formed by local discontinuities in the electric field at this interface. These discontinuities may exist due to traps, imperfections in the lattice, and the quality of the contacts. In these higher field regions the classical process of avalanche breakdown occurs. This process is shown schematically in Figure 3.

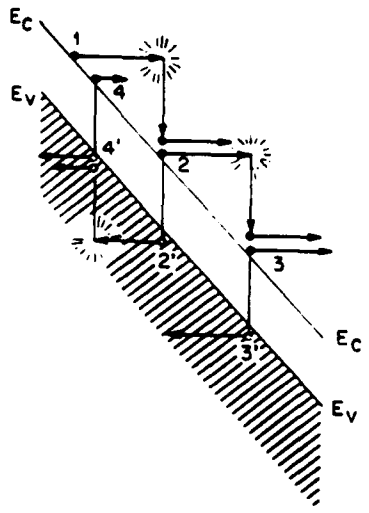


Figure 3: The Avalanche Process

Consider the electron (No.1) in the conduction band. It is accelerated by the intense local field then upon impact with the lattice creates the hole electron pair (Nos. 2 and 2'). There are now three carriers that may continue this avalanche process. It is this continual generation of new carriers that causes large currents to develop when the avalanche process occurs.

It is possible to determine the energy required for an electron to undergo the avalanche process by simply conserving both energy and momentum during these collisions.(11) It is found that the kinetic energy required for this type of avalanche process to occur is approximately:

$$E_O = 1/2\ m_1\ v_S^2 = 1.5\ Eg \qquad (1)$$

where (m_1) is the mass of the particle, (v_S) is the saturation velocity, and (Eg) is the bandgap energy. Thus, the energy required for an electron to continue this process is about 1.5 times the bandgap energy. For silicon, a much more rigorous treatment that includes the relative mobility's of the species, a value of 3.6 eV for electrons and 5.0 eV for holes is obtained.(11)

As the avalanche process propagates in a semiconductor, localized ohmic heating will occur in the channels that are formed. This ohmic heating will give rise to the thermal generation of carriers and increase the conductivity in the narrow region of the channel. The increased conductivity in this region will then permit even more current to flow, thereby further increasing the ohmic heating. This process of thermal runaway will continue down the various channels through the semiconductor until one or more of these channels eventually reach the anode during the avalanche process. It is at this point that we say that breakdown has occurred. To determine why these channels form near the surface of the semiconductor we must consider the effects of traps.

Trapping

There are four different types of traps that may occur at a metal-oxide-semiconductor interface.(11) They are interface-trapped charge, fixed-oxide charge, oxide-trapped charge, and mobile ionic charge. These traps are outlined schematically in Figure 4.

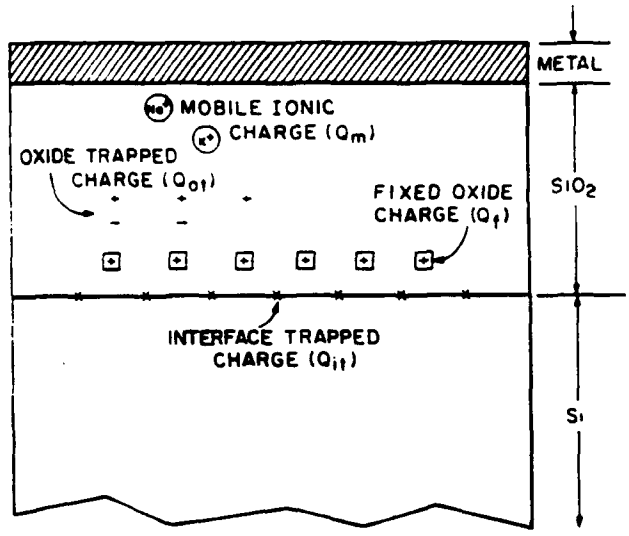


Figure 4: Various Trapping Mechanisms

Interface-trapped charges (Q_{it}) are located at the Si-SiO_2 interface and are highly dependent upon the chemical composition of the surface. The energy levels associated with these traps are located in the middle of the forbidden band gap of silicon and the density of these traps is highly dependent upon the orientation of the crystal. In the <111> crystal orientation trap densities are approximately 10^{11} cm^{-2}, while in the <100> orientation their density is only 10^{10} cm^{-2}. Most of these traps may be neutralized by low temperature hydrogen annealing.

The fixed-oxide charge traps (Q_f) are normally located within 30 Angstroms of the Si-SiO_2 interface. Their charge is usually positive and cannot be neutralized over a large variation in surface potential. It is believed that this layer forms when oxidation is stopped and many of the ionic silicon atoms have incomplete bonds. These trapped charges are usually modeled as a fixed sheet of charge at the Si-SiO_2 interface. The density of these traps is also very orientation dependent. Typical densities of these traps are about 5×10^{10} cm^{-2} in the <111> orientation and 10^{10} cm^{-2} in the <100> orientation.(11)

The oxide-trapped charges (Q_{ot}) are defined as defects in the SiO_2 layer itself. They may be created by any form of high energy electron bombardment. These traps may be positive or negative and can be located anywhere in the oxide layer. These types of traps can usually be removed by low temperature annealing.

Mobile ionic charges (Q_m) are usually alkali ions such as sodium and are mobile within the oxide during high-voltage, high-temperature conditions. These charges may move about in the oxide causing reliability problems and shifts in the capacitance vs. voltage curves of junctions.

All of these traps may affect the formation of current channels at the oxide-semiconductor interface. Interface charges may create areas where the injection of fast electrons is greater than others. The oxide trapped charges may cause electric fields that help to enhance the overall field and thus promote channel formation in that region. If the metal is biased negatively, the fixed oxide charges help to build up an initial space charge for the injection of electrons.

Trap densities are also high near the edges of semiconductors. This is probably due to the dangling bonds near the edges of the material and the absorption of gases. It is these traps that may also contribute to the formation of channels just below the surface of semiconductors. Klein (12) has also reported that trap state densities at the injection

barrier of SiO_2 may grow as large as 10^{19} cm^{-2}, due to the damage of the lattice by the breakdown current. A trap density this large may cause the oxide to transition from an insulating to a conducting state in certain regions and further contribute to channel formation.(12)

Experimental Setup

The setup for this experiment consisted of four major components: a vacuum system, a pulse forming network, various silicon samples, and measurement equipment. Each of these systems will be outlined in the following paragraphs.

Vacuum System

The breakdown characteristics of various silicon samples were investigated in an oil free high vacuum system at a pressure of 2×10^{-8} torr. The pressure was monitored using a standard ion gauge and chart recorder. A gate valve that separated the chamber from the vacuum pumps could also be closed to determine the leak-up rate of the system.

The samples were mounted in the vacuum chamber by two spherical aluminum electrodes that were 2.54 cm in diameter. Each electrode also had an on-axis recess (1.1 cm diameter and .2 cm deep) that was filled with indium metal to make good electrical contact between the silicon and the Pulse Forming Network.

Pulse Forming Network (PFN)

A Pulse Forming Network (PFN) was used to measure the samples' breakdown characteristics. The PFN was capable of delivering 100 ns pulses ranging from 3 to 18 kV. The PFN was initially triggered by a 2 volt pulse from a HP Pulse Generator. This 2 volt pulse then triggered a field-effect transistor that is biased at a 100 volts with a solid-state DC power supply. The 100 volt pulse then triggered a 5 kV pulse from a high voltage pulse generator. Finally, the 5 kV pulse triggered a variable output 50 kV DC supply which discharges across a thyratron to deliver the voltage pulse to the sample.

Silicon Samples

Three different silicon samples were used in this experiment. All the samples were cylindrical (10 mm diameter x 5 mm tall) and were processed from a supply of high purity silicon (resistivity 30 K-ohm-cm). The first sample was doped on one end with boron through ion implantation. The doping concentration was $5x10^{16}$ atoms/cm^3 and extends one micron into the sample. This doped end was covered with 1000 Angstroms of aluminum for metallization of the contacts. The other end was coated with two microns of gold for the same reason. The second sample was a pure silicon sample with both ends coated with two microns of gold. The third sample was coated on one end with a 2.5 micron layer of SiO_2 by heat treating the sample at 900 C for 8 hours in an oxygen atmosphere. This end was then covered with 1000 Angstroms of aluminum. The other end was again coated with two microns of gold.

Measurements

The voltage pulse across the sample was monitored by a 1000x high voltage attenuator located at the top of the sample. The curren` measured was proportional to the voltage drop across a current viewing resistor (CVR) located at the bottom of the sample. Figure 5 on the following page shows the sample and measurement circuit. A distinct advantage of this system is the high internal impedance of the PFN (280 ohms). This high resistance in series, limits the current delivered to the sample. High currents would lead to degradation and eventual damage of the sample.

The sample voltage and current waveforms were digitized with a 125 MHz bandwidth digital oscilloscope at a 100 MSamples/sec digitizing rate. The data was then transferred to a laboratory computer and stored on disk.

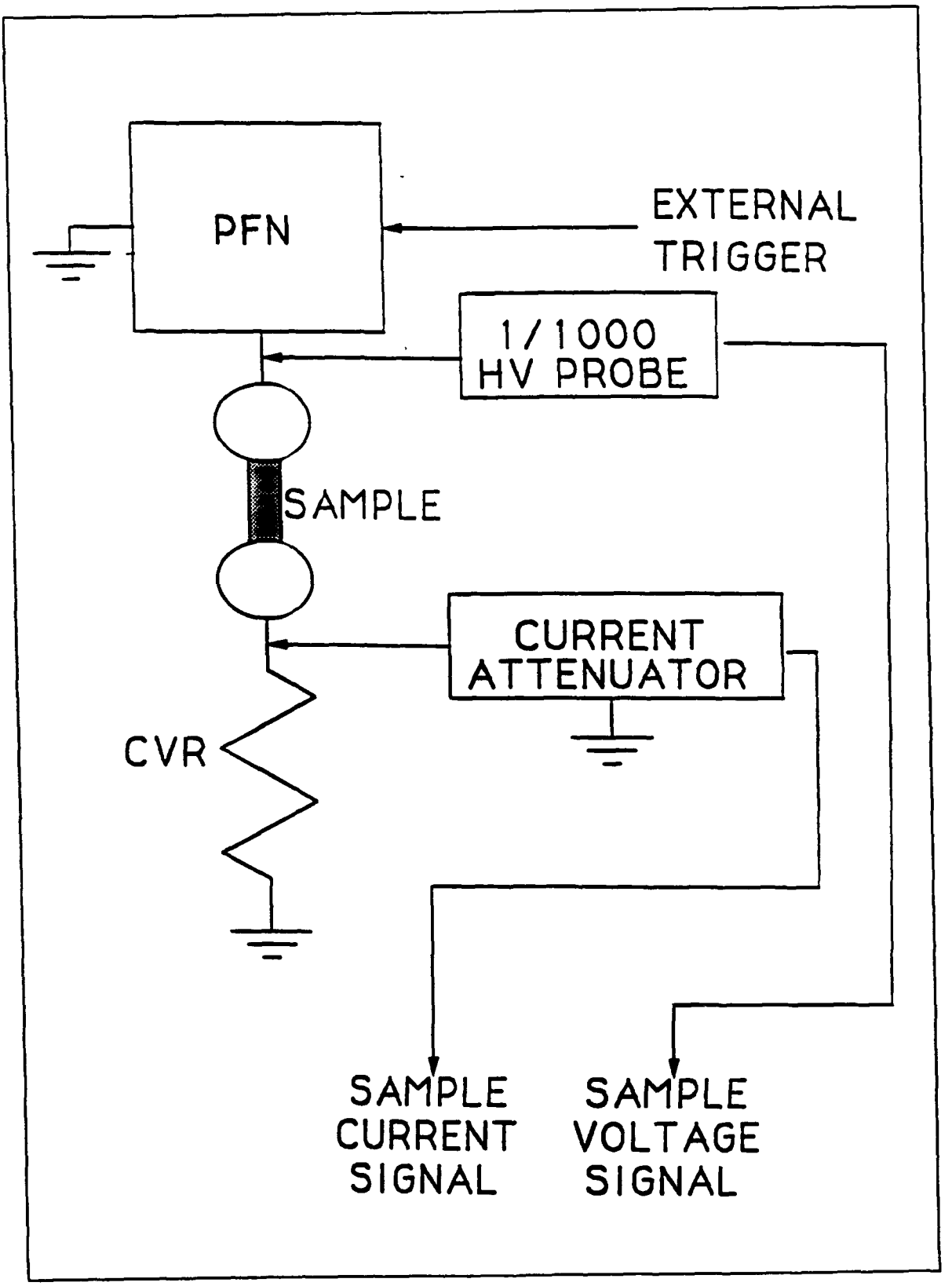


Figure 5: Experimental Setup

Results

Typical Voltage and Current Curves

A typical set of voltage and current curves collected with the digitizer are shown in Figures 6 and 7. In each of these figures the top curve is the voltage pulse in kilovolts and the bottom curve is the current in milliamps. In Figure 6, the voltage pulse peaks at 2.8 kV and has a duration of almost 200 ns. The first peak in the current pulse is the displacement current, due to the capacitance of the junction. The second peak, which is the conduction current, coincides with the voltage peak and has an amplitude of 98 milliamps. It is also important to note the rise time and duration of the current pulse. In this figure the current rise time is about 50 ns and the FWHM width is about 100ns. Currents with these characteristics are usually bulk conduction currents in which the current is distributed across the sample.

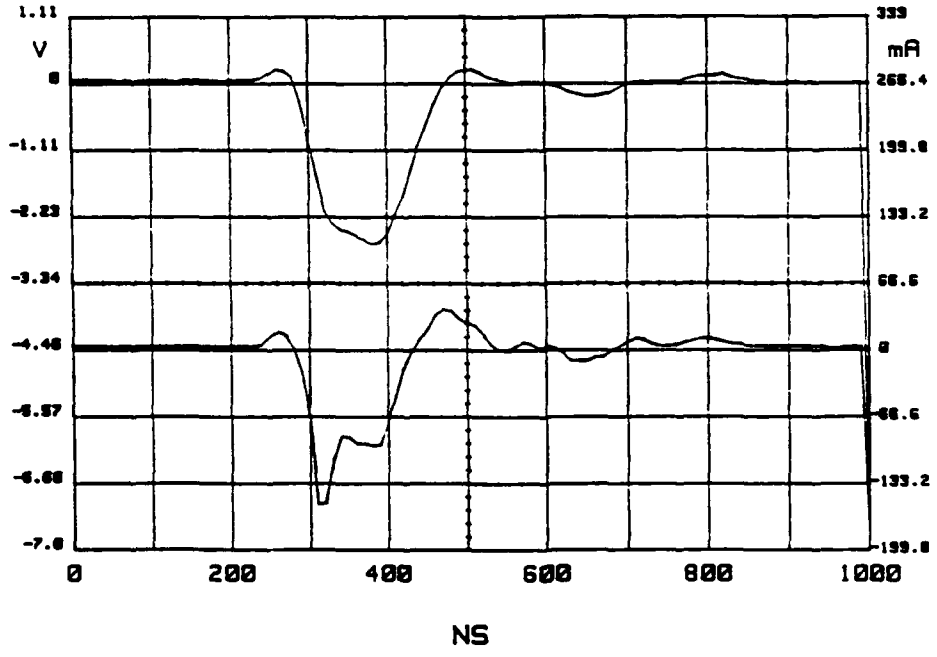


Figure 6: Voltage and Current Curves for a Conduction Current

In Figure 7, the voltage pulse peaks at 15.1 kV and has a duration of 150 ns. Notice that the voltage waveform is also slightly clamped towards the end of the pulse due to the limitations of the power supply. The peak of the current pulse is now delayed 60 ns and has a peak of 16.5 amps. The delay time is considered to be associated with the build up of the local electric field at the interface before breakdown actually occurs. This local electric field will generally tend to increase as more electrons are injected into the sample. It may also decrease for a short period of time as recombination and diffusion take place. The rise time of the current pulse is also faster (35 ns) and the width is smaller (75 ns FWHM). This current is characteristic of the avalanche process in which electron multiplication occurs causing large currents to develop and flow very quickly down the channels formed in the silicon.

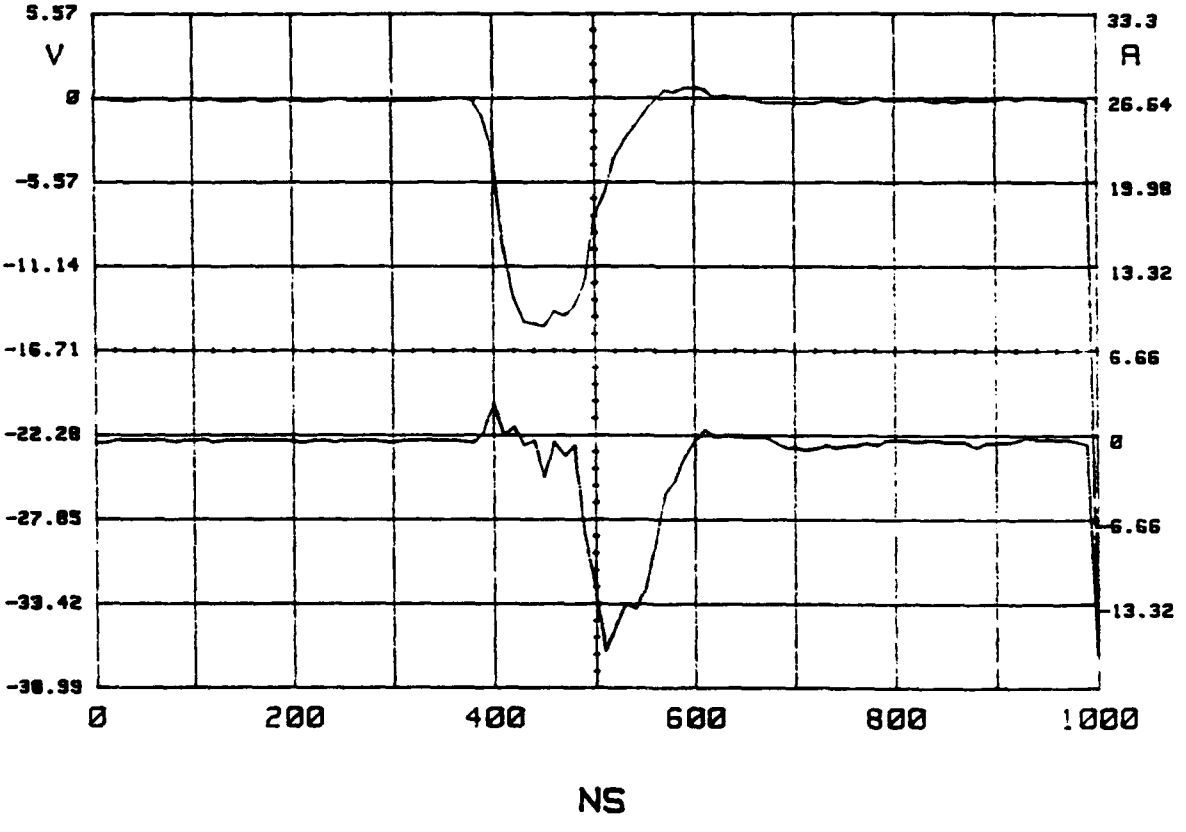


Figure 7: Voltage and Current Curves for a Breakdown Current

Typical I-V Curves

A typical current vs. voltage curve constructed from measurements such as those in Figures 6 and 7 is shown in Figure 8. Notice that the curve is quite linear until approximately 9 kV, after this point the slope increases dramatically. It is at this point that the breakdown region begins. Before the breakdown region, the sample appears very ohmic with a linearly increasing current, the slope in this region can be measured to determine an effective impedance of the sample. After the breakdown region a "logarithmic fit" can be used to determine the approximate relation at which the current is increasing with voltage. Also notice the increase in the statistical fluctuations of the measurements as the voltage across the sample increases, illustrated by the bars in the following graph. This is due to the fact that the breakdown process is markedly statistical in nature and breakdowns occur a greater percentage of the time at higher voltages. When breakdowns do occur at higher voltages the range of measured currents can be even greater than the distributions shown in the following graph.

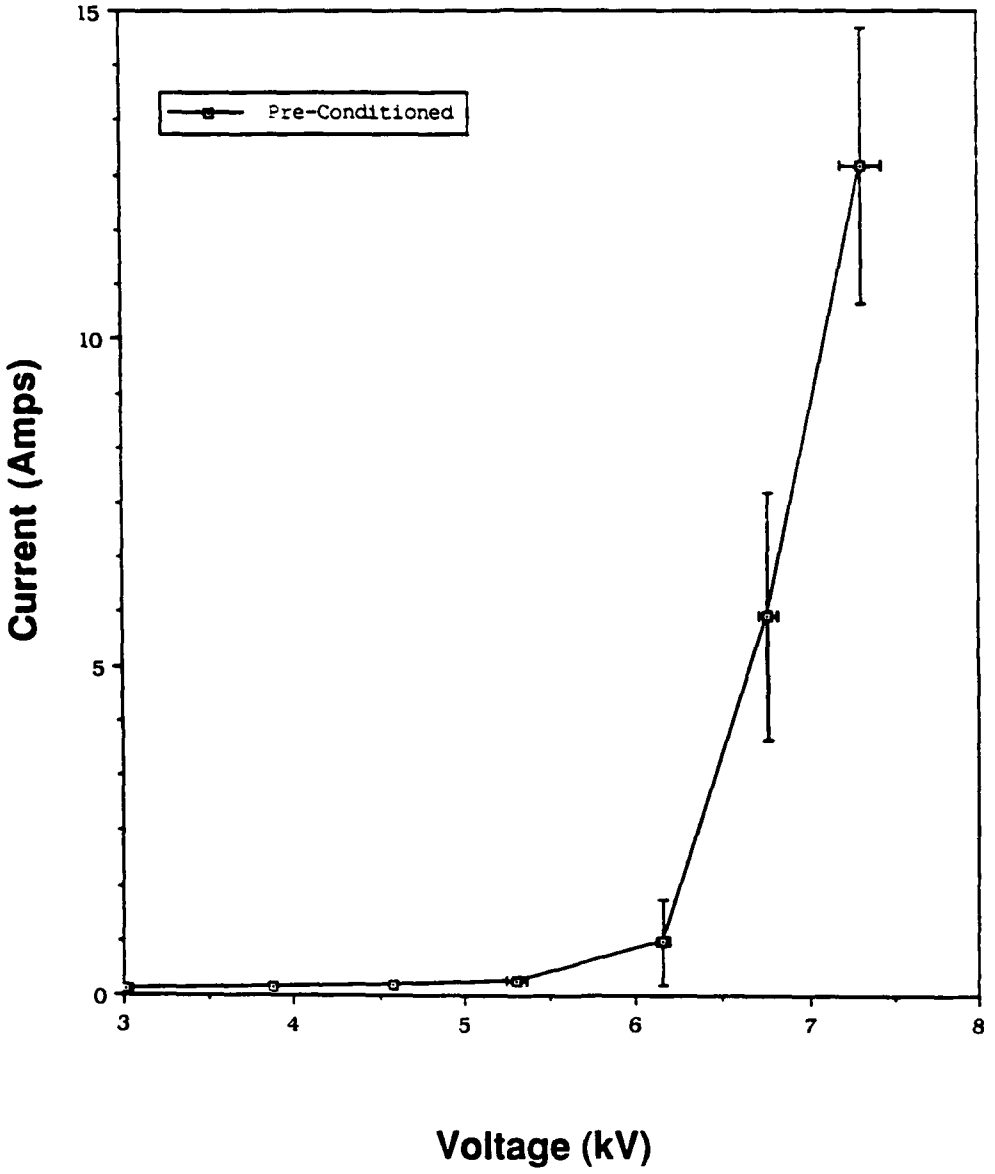


Figure 8: Typical Current - Voltage Curve with Statistical Fluctuations

A sequence of current verse voltage curves for a sample are shown in Figure 9 in order to demonstrate the effect of "conditioning". The set of data labeled "Pre-conditioned" was the first set of data collected from this sample. Notice that breakdown occurs around 9 kV. After successive voltage pulses near the breakdown potential were applied, the I-V curve typically shifts toward higher voltages, as shown in the second data set labeled "Conditioned". Although it is not completely understood, this process is known as the "conditioning" of a sample. It is believed that this conditioning effect primarily occurs as a result of water vapor being desorbed from the surface of the sample. The water vapor provides a path of lower resistance near the surface of the sample in which the breakdown current may flow. After successive voltage pulses the water vapor is eventually desorbed from the surface and the breakdown potential increases. In the third set of data labeled "Air Fill," the sample was again exposed to the room air containing water vapor and a slight reduction in the breakdown potential occurred, consistent with the water vapor hypothesis. After further conditioning, or removal of the water vapor, the breakdown potential achieved even higher values as shown in the "Re-Conditioned" data.

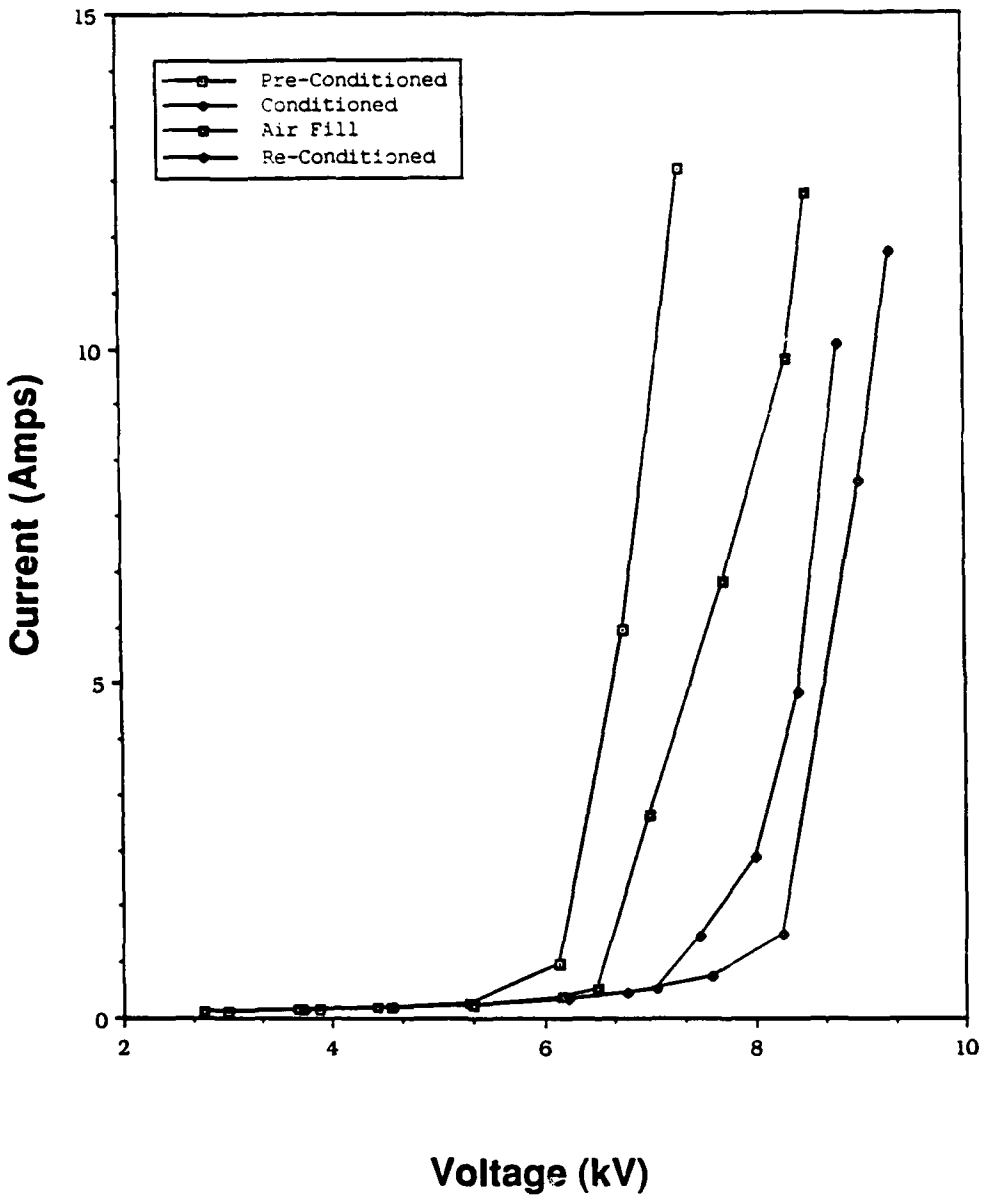


Figure 9: Typical Set of Current-Voltage Curves

Data Collection

There were five major measurements taken to evaluate the breakdown characteristics of the various samples. The measurements taken were: the hold off potential, the effect of conditioning on the sample, the impedance of the sample, the power dependencies of the I-V curves for each sample, and the delay of the current pulse. The results of these measurements are presented in tabular form in Figure 10.

	Boron at the Cathode	Boron at the Anode	Pure Silicon	Oxide at the Cathode	Oxide at the Anode
Breakdown Potential (kV/cm)	20.4	22.0	16.0	21.0	36.6
Effect of conditioning	Minimal	No loss of conditioning	Minimal	Normal	N/A
Impedance	24.0 K	39.5 K	26.0 K	8.6 K	30.9 K
Power Dependency					
Low	1.05	.94	1.20	1.60	.98
High	11.10	24.10	10.20	6.50	1.65
Average Delay Time	80 ns	70 ns	85 ns	100 ns	N/A
Pressure Change	Pressure change observed	Pressure change observed	Large pressure change	Pressure change observed	N/A
Other	visible emission	visible emission			excellent switch

Figure 10: Results of Measurements for the Various Silicon Samples

For the case of the pure silicon sample and the configuration with the oxide layer at the anode, the pressure changes at breakdown were also measured.

The breakdown potential was determined from the I-V curves of the various samples as presented in Appendix A. As shown in Figure 8, the onset of breakdown is the point on the curve where the current began to rise rapidly and no longer behaved like an ohmic current. The effect of conditioning on the sample was then determined by the resultant shift of the breakdown potential when the sample was exposed to the water vapor in the room air.

The impedance of the samples was determined by a linear fit to the low-voltage regime of the I-V curves. The I-V value (0,0) was also included in this fit. The slope of this line was then used to calculate the effective impedance of each sample in the various configurations. The linear fits and calculated slopes for all the samples are presented in Appendix B.

The power dependencies of both the low and high voltage regimes of each of the samples I-V curves were determined by using a logarithmic curve fitting routine. This routine determined a single power that best described the characteristic rise in the current as the voltage was increased. This power dependency gave an estimate of the effective gain that occurred in a given sample. These power dependencies are shown in Appendix C.

Next, the average delay time of the current pulse during breakdown was measured as in the examples of Figures 6 and 7. The delay time was determined by the time between the first voltage peak and the first current peak.

For the pure silicon sample, oriented with the oxide layer at the anode, the pressure changes during breakdown were also measured. These measurements were made by first observing the normal leak-up rate of the vacuum system. This was easily accomplished with a chart recorder connected to the ion gauge. Then a valve that

separated the vacuum pumps from the chamber was closed and the pressure change over time was measured. Next, voltage pulses were triggered with the main valve closed and deviations from the normal leak up rate were observed. Pressure changes as small as 4 x 10^{-10} torr were measurable in this configuration. The results of these pressure changes for the pure silicon are presented in Figure 11. For the case of the oxide at the anode no pressure changes were observed.

These pressure change measurements were very important because if channel formation was occurring, the current through the bulk of the sample would be constricted to very narrow channels. These narrow channels would have very large temperature changes associated with them and some thermal desorption would likely occur. It is believed that this thermal desorption then led to the pressure changes that were measured.

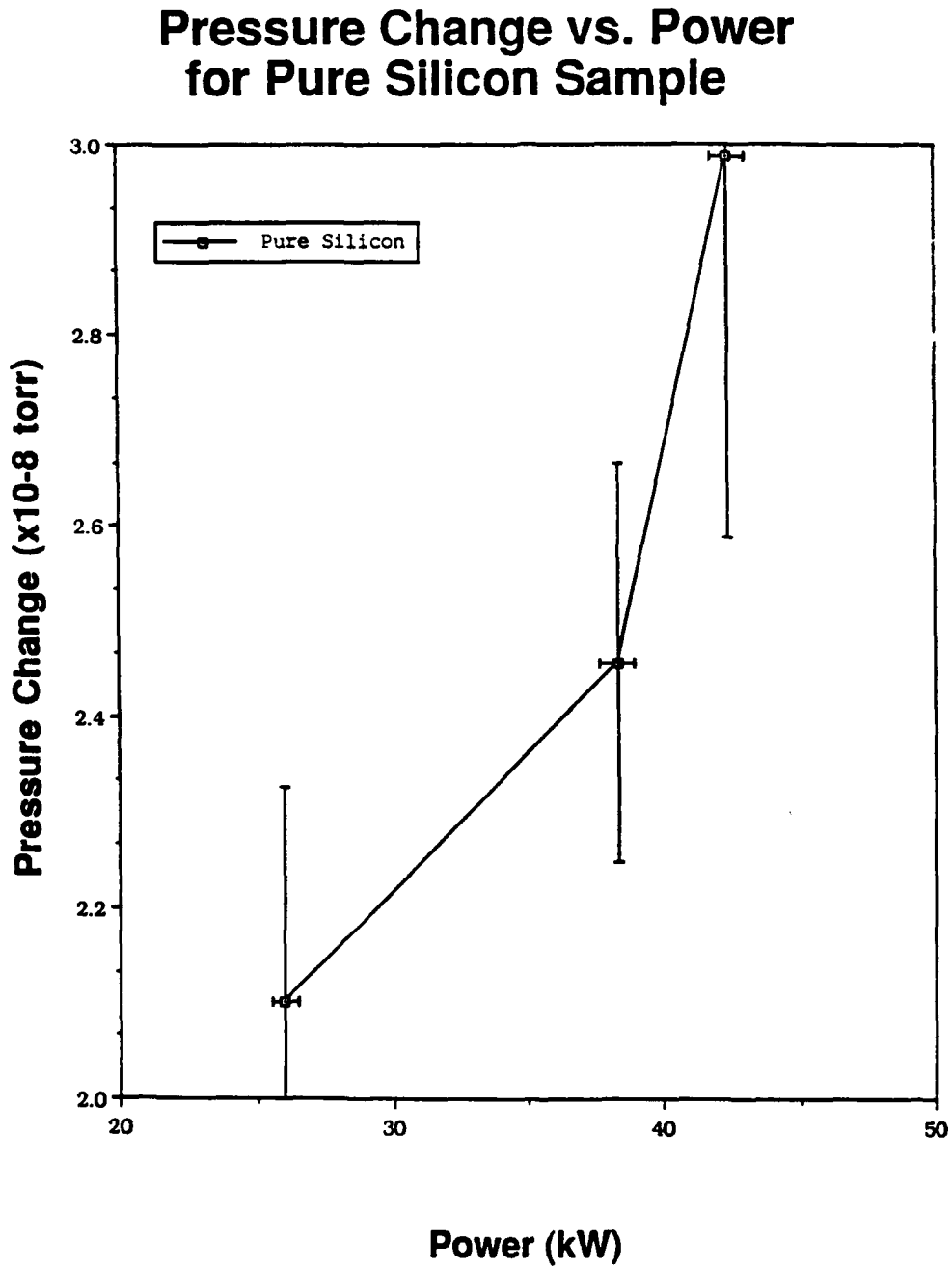


Figure 11: Pressure Changes at Breakdown of Pure Silicon

Discussion

The following section contains actual breakdown I-V curves for the five samples that were considered: boron at the cathode, boron at the anode, pure silicon, an oxide layer at the cathode, and an oxide layer at the anode. Each of these curves is presented along with a possible explanation of the results that were obtained in each measurement.

Boron at the Cathode

The boron doping reduced the effective impedance of this sample to a value slightly lower than that of the pure silicon sample. In this orientation the breakdown potential increased by 4.4 kV/cm. This increase may have occurred due to the recombination of electron-hole pairs in the boron at the cathode. This would reduce the space charge at the interface and thus increase the breakdown potential. Recombination may have also been responsible for the visible emission that was observed. This visible emission may have created numerous other electron hole pairs and these new carriers may have contributed to the very large current spike in Figure 12.

The 80 ns delay time is associated with the time in which the space charge builds up at the junction, until reaching a potential that was high enough for breakdown to occur. The high power dependency of the breakdown curve and the characteristics of the current pulse (40 ns rise time and 75 ns FWHM) also show evidence of an avalanche breakdown.

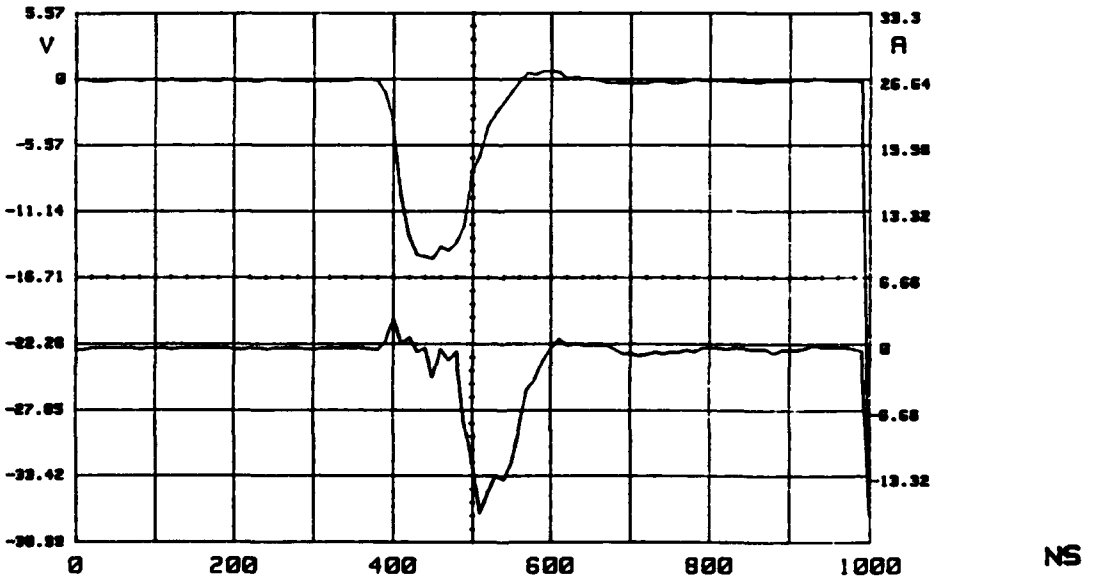


Figure 12: Typical Breakdown I-V curve with Boron Doping at the Cathode

Boron at the Anode

In this configuration the breakdown potential of the silicon was increased to a slightly higher value of 22 kV/cm. This was probably because the voltage drop across the sample was now distributed across the junctions at both the anode and the cathode. With a lower voltage drop at the cathode it was less likely that a large enough space charge could build up to cause channel formation. Notice in Figure 13 that the current is still characteristic of a typical breakdown current (75 ns delay, 35 ns rise time, and 100 ns FWHM width).

A recombination light was also observed in this configuration. This may have led to the very high power dependency (24.1) that was fitted to the high voltage I-V curve. It is possible that in this configuration the initial electrons were slowed down enough by passing through the bulk of the silicon that they were more likely to recombine with the boron at the anode. This recombination light causes a greater number of electron-hole pairs to be generated throughout the sample and thus increases the number of carriers and contributed to the high power dependency measured.

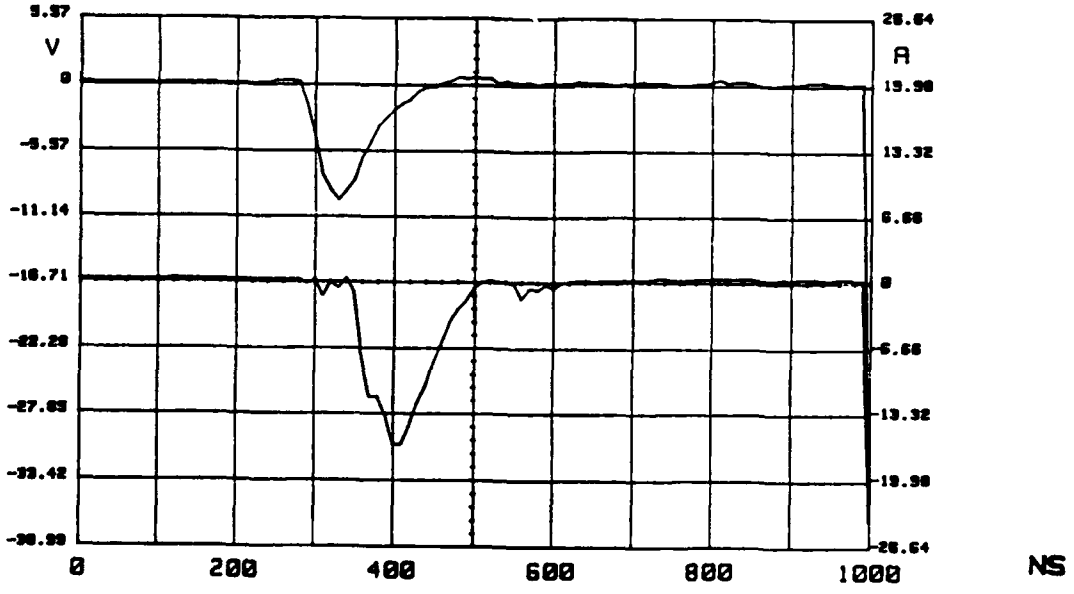


Figure 13: Typical Breakdown I-V curve with Boron at the Anode

Pure Silicon

For this sample it was not very apparent at first that breakdown had occurred, as shown in Figure 14. Upon further inspection it was clear that the current pulse was quite delayed (80 ns) and that the voltage pulse was clearly clamped. Both of these are very positive signs that a breakdown had in fact occurred. The high power dependency of 10.2 is also good evidence that an avalanche breakdown had taken place.

The best evidence of channel formation in the case of pure silicon is the large changes in the pressure at breakdown. At a power of 42 kW, a pressure change of 3 x 10^{-8} torr was observed. If this current was distributed across the bulk of the sample a temperature rise of only a few degrees would occur. This current must have been localized to very narrow channels in which the large temperature rise was able to cause thermal desorption. This thermal desorption was then measured as a pressure change.

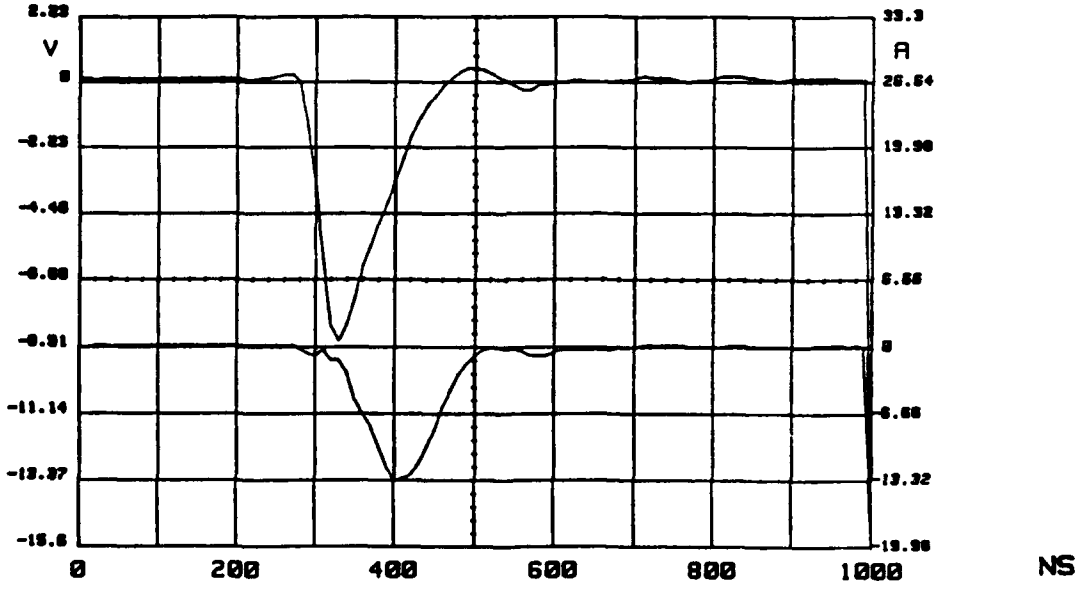


Figure 14: Typical Breakdown I-V curve for Pure Silicon

Oxide at the Cathode

In this configuration the breakdown potential was once again greater than that of pure silicon by 5 kV/cm. A small initial space charge probably built up quickly with the presence of an oxide layer at the cathode. The total electric field now had to reach even higher levels now in order to accelerate the electrons through the oxide. The very long delay time (100 ns), probably corresponded with the time it took for the space charge to build up to greater levels until the total electric field was high enough to cause breakdown across the oxide layer. When the breakdown finally occurred it was a very fast, sharp breakdown, characteristic of an avalanche breakdown. In this configuration the majority of the voltage drop occurred at the cathode. This conclusion is partially supported by the low voltage dependency of 1.6 that is characteristic of space charge limited conduction.(11)

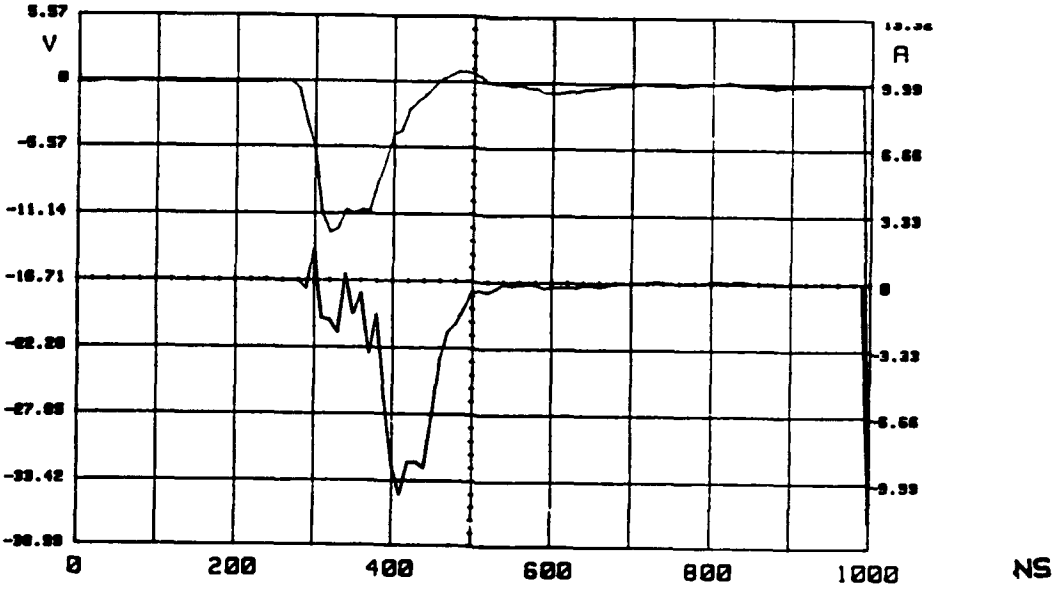


Figure 15: Typical Breakdown I-V curve with Oxide at the Cathode

Oxide at the Anode

The best characteristics were obtained in this configuration. The sample did not break down with fields as high as 36.6 kV/cm. This sample probably exhibited the highest breakdown potential because the voltage drop was divided between both junctions, leading to smaller fields at both ends of the sample. These smaller fields were then less likely to inject electrons into the sample initiating breakdown.

The lack of a pressure change at high voltages also supports the contention that no channels were formed in this case. If these narrow channels were to form, intense ohmic heating would have occurred leading to the desorption of particles from both the lattice and from impurities in the lattice. A pressure increase would have then been noticed with these extra particles in the vacuum system.

In this configuration the silicon sample was briefly tested to see how it functioned as a PCSS. When a 2 mJ Nd:YAG laser was used to illuminate the sample just before the voltage pulse, the effective impedance of the sample decreased by three orders of magnitude. The sample in this configuration thus made an excellent PCCS.

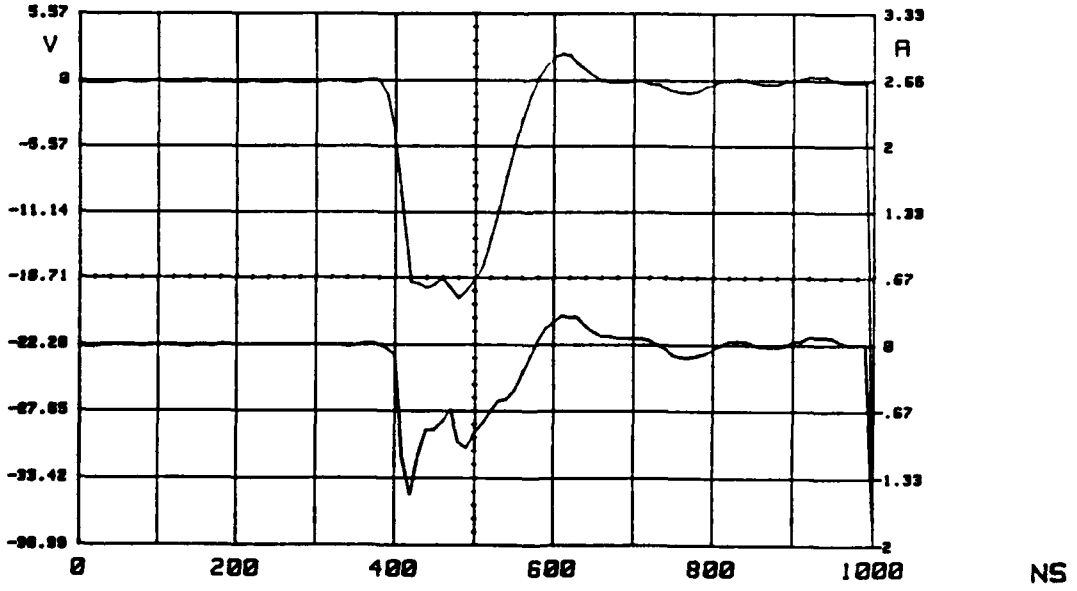


Figure 16: Typical I-V curve with Oxide at the Anode

Summary and Conclusions

There were two very important results obtained in this experiment. First, that junctions play a very important role in determining the breakdown characteristics of semiconductors. This result is supported by the theory of semiconductor breakdown presented in this paper. It describes how the discontinuities at the junctions and at the metal-semiconductor interface due to traps and lattice imperfections lead to a non-homogeneous space charge. This space charge then leads to a non uniform electric field at the junctions. This field may increase as more electrons are injected into the sample or it may decrease as recombination and diffusion take place. It is then in the regions of enhanced electric field that some initial electrons are injected into the semiconductor to begin forming channels. This process of channel formation is further perpetuated by thermal run away. Thermal run away occurs because as a channel is heated its conductivity increases, as the channel becomes more conductive, more electrons follow down this path, leading to even more ohmic heating. These channels then continue to form down the sample until one or more of them reach the anode. It is at this point that breakdown occurs. It was found that the junction characteristics can affect the breakdown potential of a bulk silicon sample by greater than a factor of two.

In the case of a pure bulk silicon sample, the breakdown potential was found to be approximately 16.0 kV/cm. In all of the other cases tested, with boron and oxide dopings at both the cathode and the anode, it was found that the breakdown potential tended to increase. The smallest increase was that of a boron doping at the cathode where the breakdown potential was 20.4 kV/cm. The best results were obtained when an oxide layer was placed at the anode. In this configuration the sample did not breakdown even with fields as high as 36.6 kV/cm. It was this characteristic that made it a good candidate for a photoconductive semiconductor switch.

The second important result of this experiment was the operation of a PCSS when an oxide layer was placed at the anode of the sample. This sample may have had a high breakdown potential because a large voltage drop was obtained at both the cathode and the anode. This would lead to smaller fields at both regions and the charge injection would not be very great. When a 2 mJ Nd:YAG laser was then used to illuminate the sample, a large number of electron-hole pairs were created providing many more carriers to support a current through the sample. The effective impedance of the sample in this configuration decreased by three orders of magnitude making it an excellent switch.

Figure 10 on page 22. provides a tabular summary of the results obtained in this experiment. The results presented in this chart will be referred to in the following paragraphs.

The effect of conditioning was very peculiar. In the case of boron at the anode, no conditioning was lost when it was exposed to the water vapor in the room air, as the other samples did as shown in Appendix A. This was a very unexpected result and it is not clear why it occurred. In the other samples in which breakdown occurred, minimal to normal effects of conditioning were observed.

Another measurement taken, the effective impedance of the samples, did not prove to be a very useful characteristic and no correlation with breakdown was observed. It was noted though, that in the case of the boron doped samples, a rectifying junction was created as was expected from doping the junction in this manner.

However, the low voltage power dependency data, did prove to be quite useful. In the case of the oxide at the cathode it was observed that the current was more space charge limited rather than ohmic, as in the other samples. This helped to support the theory that the majority of the voltage drop was occurring at the cathode of the sample. The high fields in this region then led to the injection of electrons that began the process of channel formation.

The most useful data in determining the process of breakdown was the pressure change. Although accurate measurements were only made in two samples, pressure changes were noted in the other three cases. All the samples exhibited a pressure change except for the case of the oxide at the anode. A pressure change indicated that a thermal desorption of particles was occurring. For this process to occur, ohmic heating much greater than is possible through bulk conduction must have taken place. This was very convincing evidence that channels were formed in all the cases except for the oxide at the anode.

An interesting result was obtained by correlating the breakdown potential, the delay time, and the high voltage power dependency. The following chart contains this information on the four samples that exhibited breakdown.

	Breakdown Field kV/cm	High Voltage Power Dependency	Current Delay Time at Breakdown (ns)
Boron at Anode	22.0	24.1	70
Boron at Cathode	20.4	11.1	80
Pure Silicon	16.0	10.2	85
Oxide at Cathode	21.0	6.5	100

Figure 17: Relationship Between Breakdown Characteristics

Notice in the previous chart that as the power dependency decreases, the delay time increases. The breakdown potential also decreases except for the case of the oxide at the cathode. This result means that as the time required for the space charge or total electric field to build up across the interface region increases, the process resulting in breakdown becomes less efficient as a multiplication process. This may be yet another effect of the junction. Suppose the junction is such that it takes a long time for the space charge to reach its maximum value, this could occur when there is a large amount of initial recombination. In this case the total electric field will take longer to reach a value in which channel formation may begin to occur at the interface. This is probably what is happening in the case of the oxide layer at the cathode. The majority of the voltage drop will then occur in this region, leaving a smaller electric field across the bulk of the sample. In this reduced electric field it is now less likely that a multiplication process will occur and the high voltage power dependency is reduced.

It was also interesting to note that the breakdown potential decreased as the delay time increased. As the delay time increases, the local electric field at the junction may have had more time to build up. As this local field becomes higher the probability of injecting an electron becomes greater and the possibility of channel formation is increased.

This work attempts to explain the effect of junctions on semiconductor breakdown through the process of channel formation. The data collected thus far tends to support this hypothesis, although much more work in this area is necessary to extend these results and gain a better understanding of the breakdown process in semiconductors.

Recommendations for Further Study

There are three major areas of this experiment that need to be further investigated: the visible emissions, the pressure changes, and modelling the channel formation process. The visible emissions from the boron doped samples were assumed to be recombination light. This light must be further evaluated in terms of its timing with electron injection, its wavelength, and its intensity as a function of power deposited into the sample. If this light is simply recombination light it would occur before breakdown, have a specific range of wavelengths, and its intensity would vary with the number of electrons injected into the sample. If this visible emission is some type of flashover it would occur just at breakdown and have a very broad range of wavelengths. It is only through very thorough experimental analysis that this emission can be verified as a recombination light and not a simple a flashover phenomenon.

The pressure change measurements of the pure silicon and silicon samples with an oxide layer at the anode were a very good indicator of thermal desorption and thus ohmic heating and channel formation. In the case of an oxide layer at the anode, no pressure changes were observed and thus it was assumed that no channel formation was occurring. It is recommended that these measurements be made on the other samples to help determine whether channel formation or bulk conduction is occurring through the sample. If bulk conduction is occurring in any of the other samples it would be expected that minimal ohmic heating would occur and no thermal desorption or pressure changes would be measured.

It would also be advantageous to obtain Scanning Electron Microscope (S.E.M.) Photographs of the samples in the various configurations to see if channels were in fact formed as others have reported.(9) It is possible that at lower power settings that no permanent channels or lattice dislocations may be present. In this case the channels may

be simply choosing the path of greatest conductivity and at low currents not damaging the crystal lattice.

Some recent advances in bandedge absorption experiments may enable one to view the process of channel formation as it occurs. In this type of measurement, one laser is used to illuminate the sample with energies in the long wavelength edge of the band gap. Another laser is then used to measure the increase in the absorption of the material resulting from an increase in the local electric field. This absorption that occurs in the region of the channel as it is formed is then imaged on a CCD camera and analyzed by means of a PC. Although this technique is quite complex it is capable of yielding temporal changes in the material as a channel is formed.

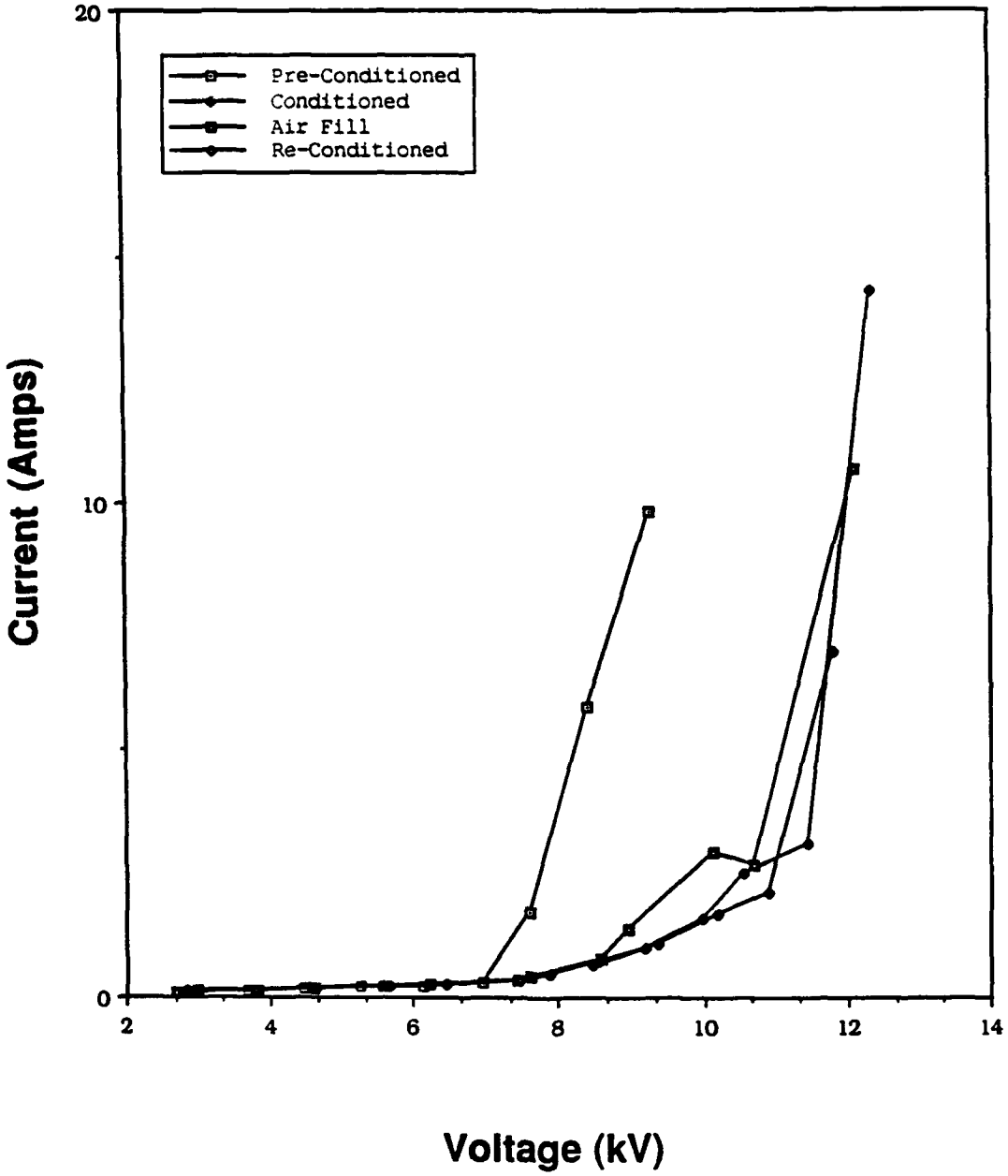
A more difficult problem is to try to numerically model the process of channel formation and determine the role that junctions play in the breakdown of semiconductors. An attempt at this will probably not be possible until more data has been collected and the conditions under which channel formation occurs are better understood. If the visible emission previously discussed is found to be a type of flashover, then the conditions under which channel formation occur may even be harder to identify. If the emission is due purely to recombination then the conditions under which this recombination occurs and the parameters that affect it will have to be investigated more closely.

Another very difficult problem in modeling the process of channel formation will be in characterizing the channels themselves. Since the channel formation process is very statistical in nature, a large amount of data must be collected to see if any trends or distributions can be spotted in the various configurations. It is data such as this that may help explain the conditions under which channel formation is most likely to occur.

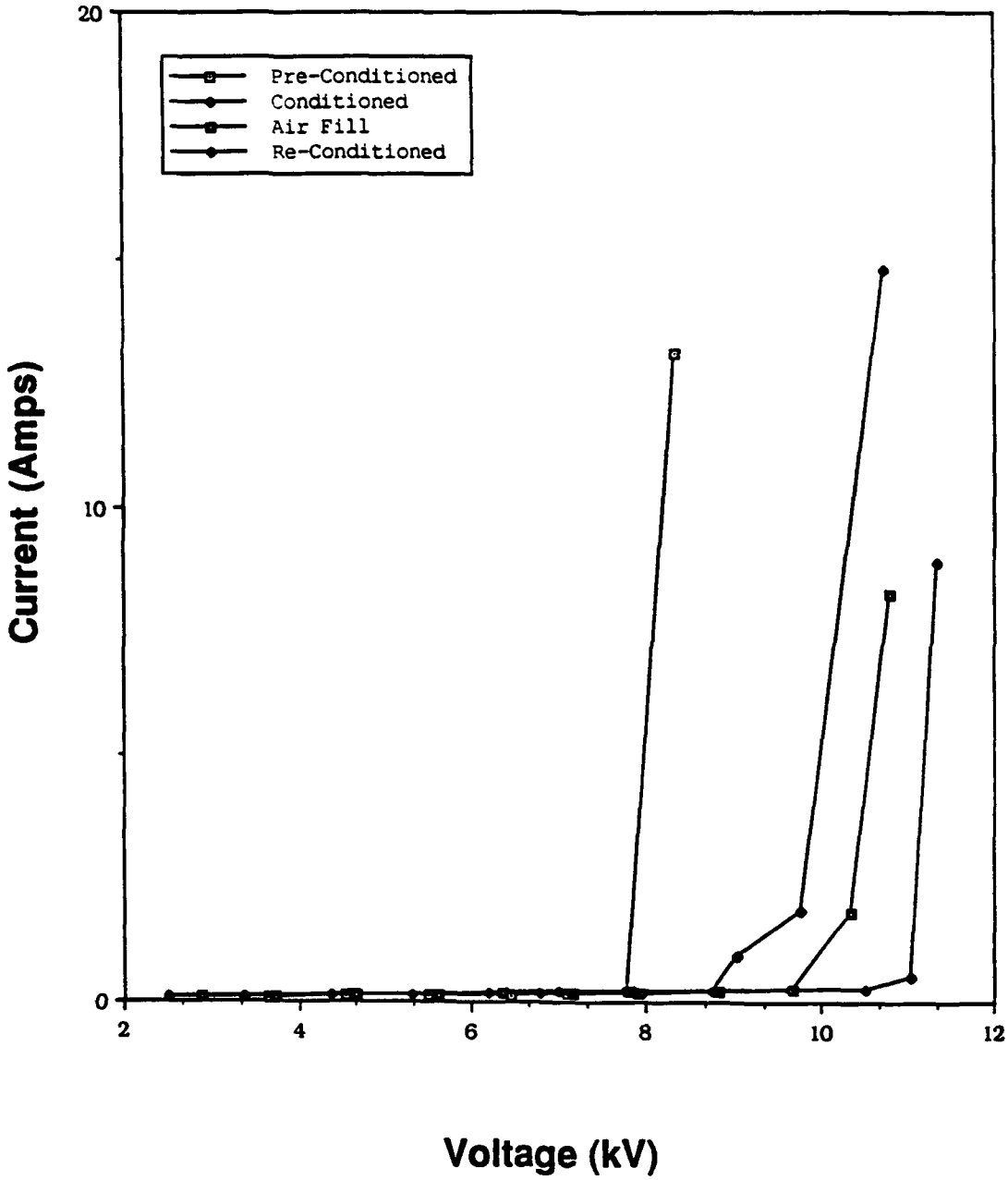
Appendix A

Complete Set of I-V Curves

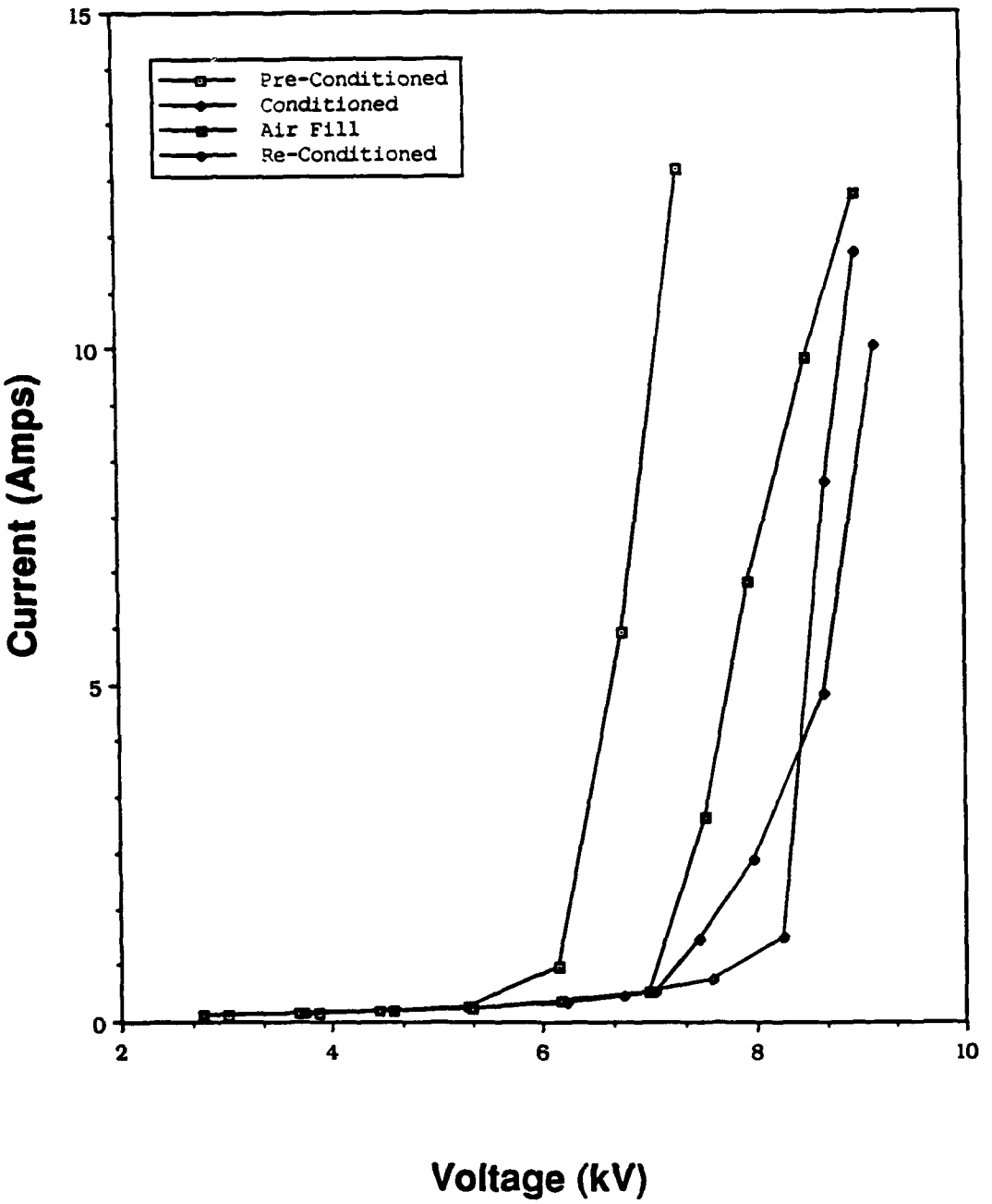
Boron at Cathode



Boron at Anode



Pure Silicon



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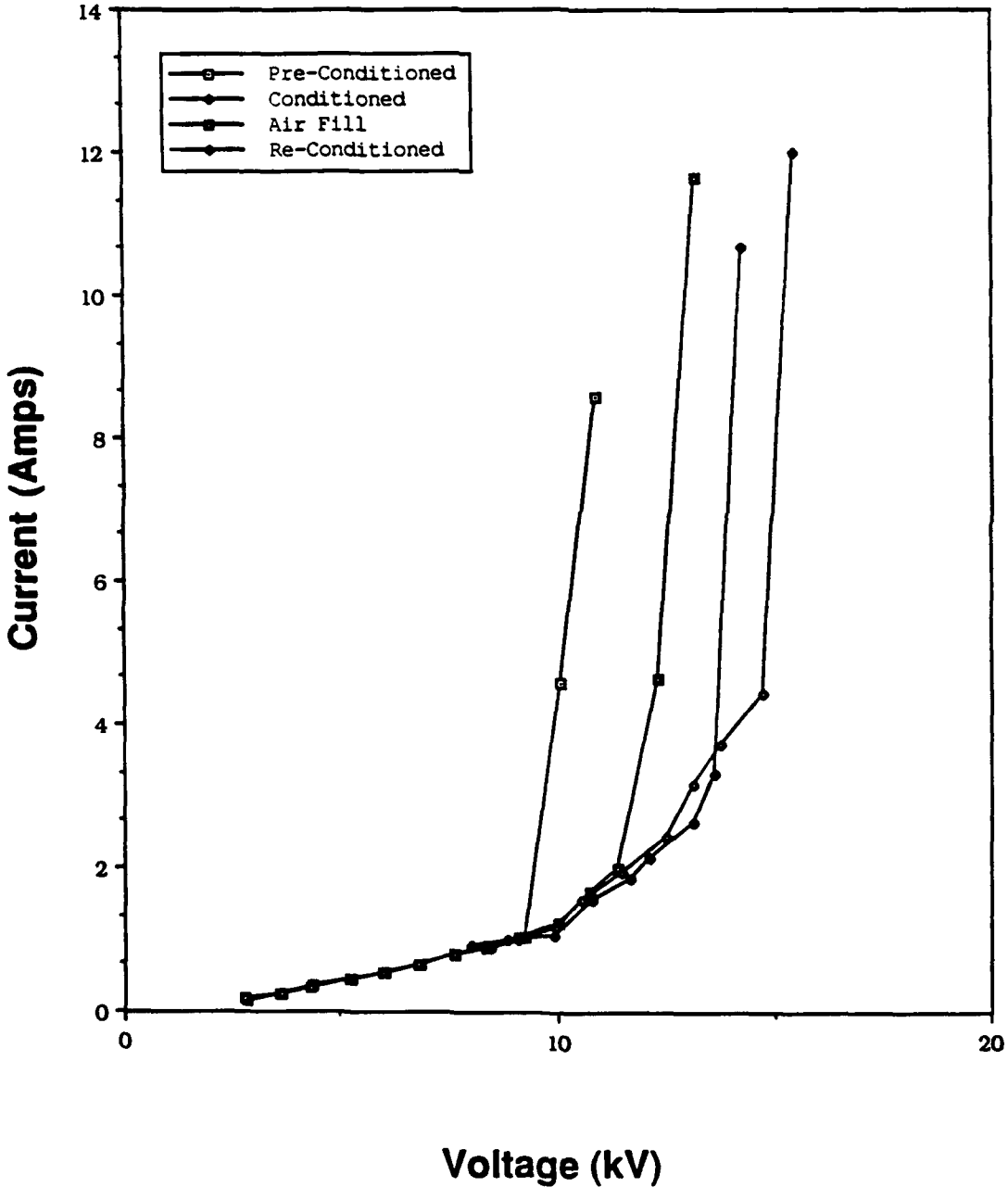
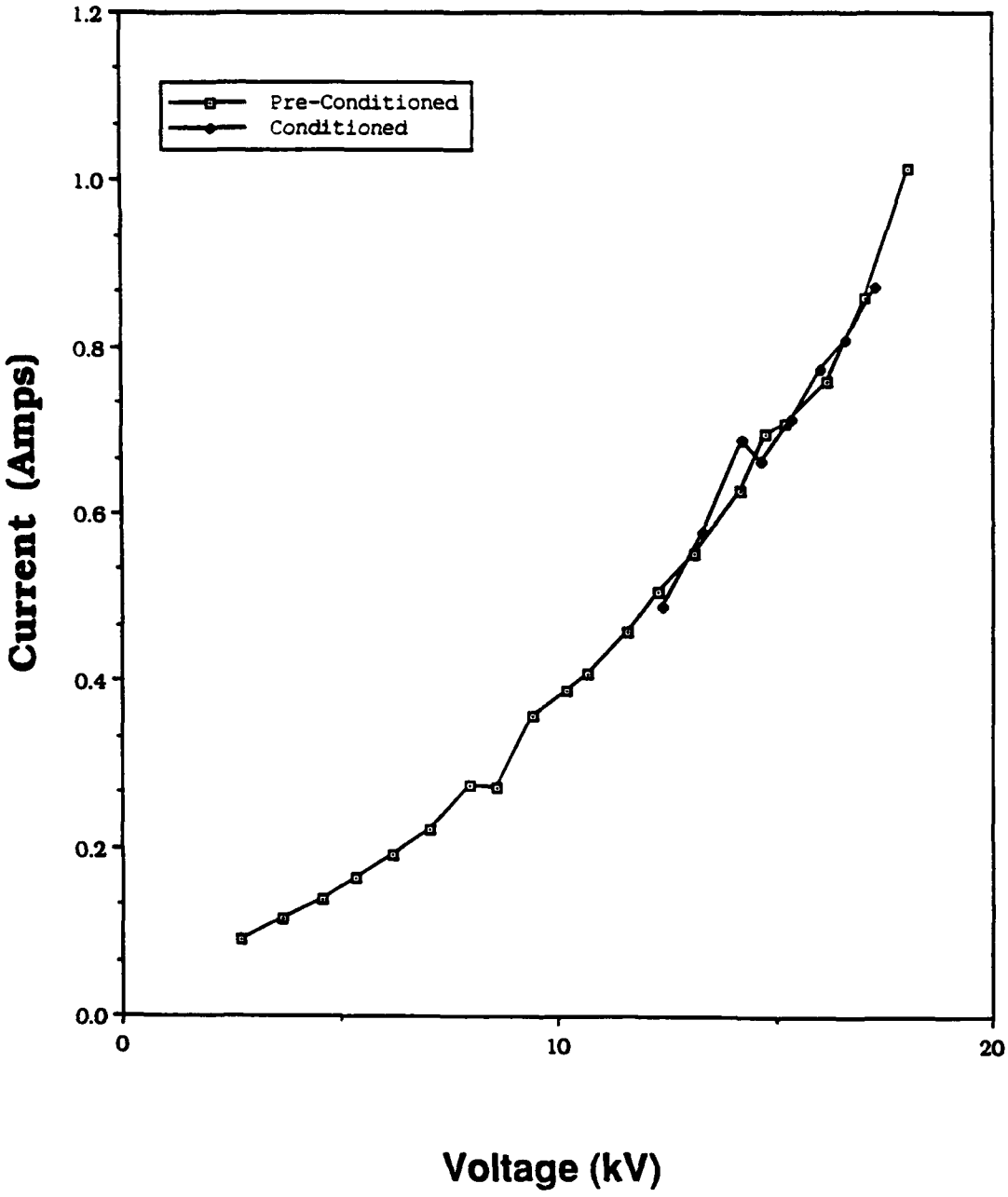


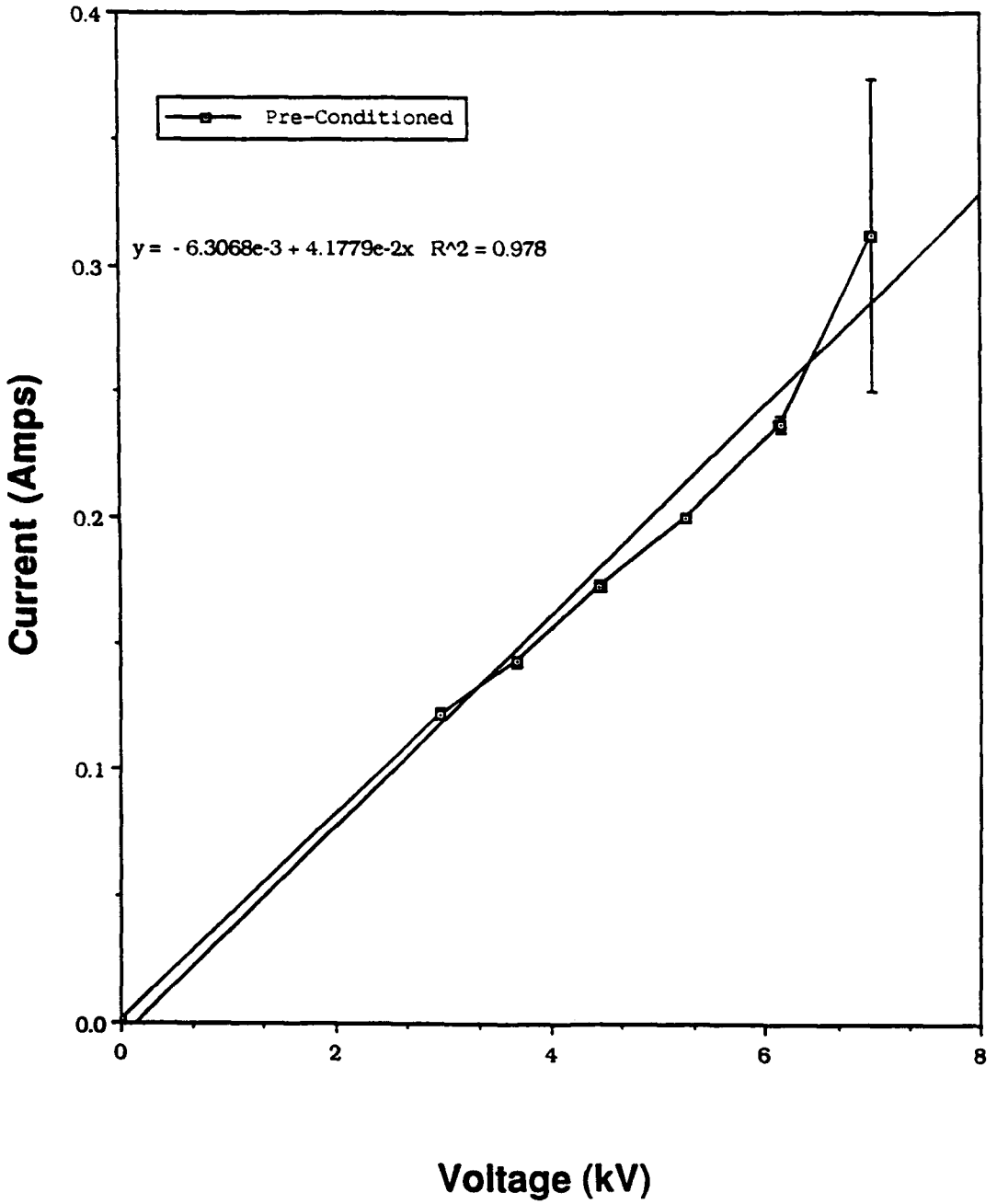
Oxide at Anode Data



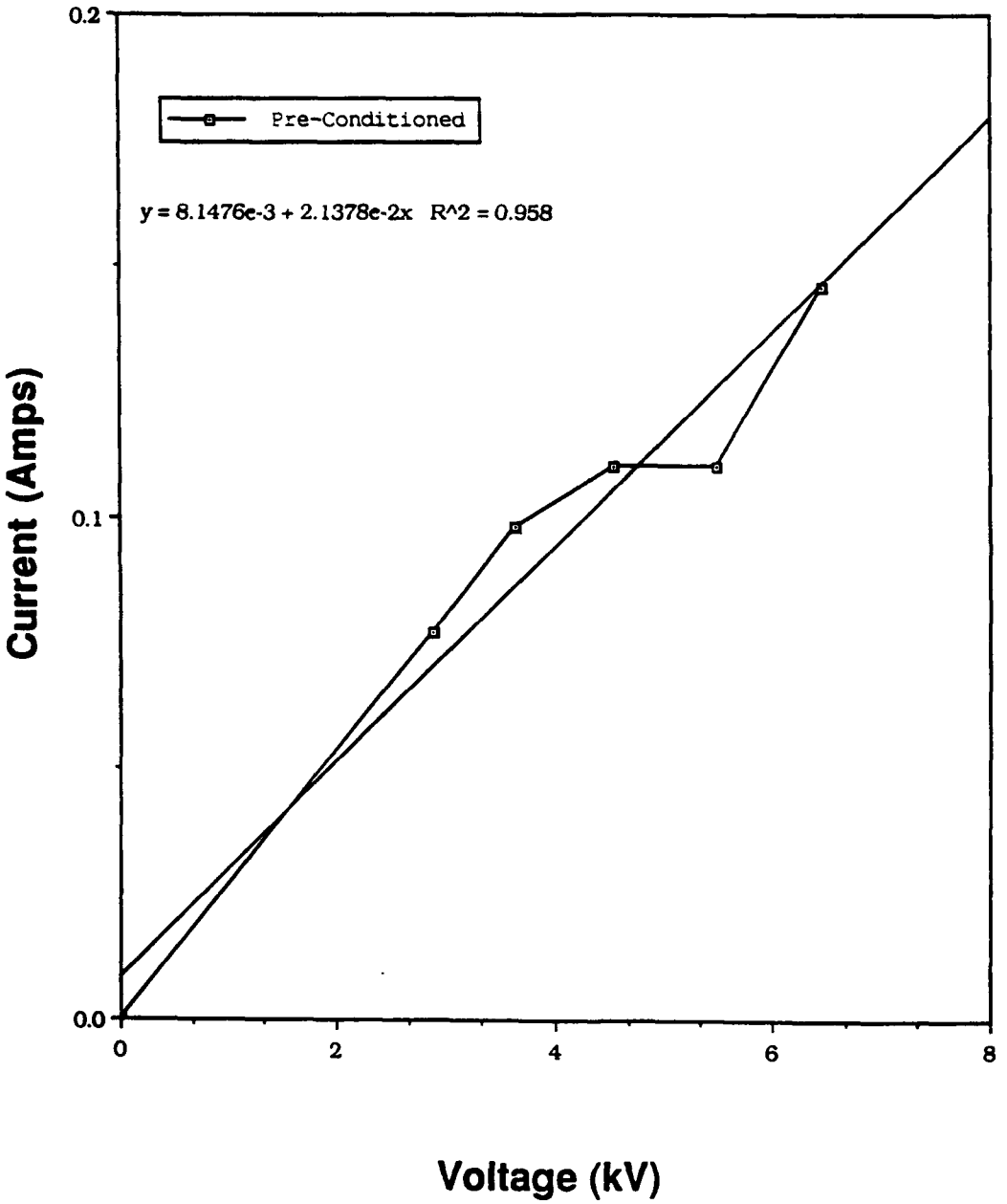
Appendix B

Low Voltage I-V Curves with Slope

Boron at Cathode



Boron at Anode



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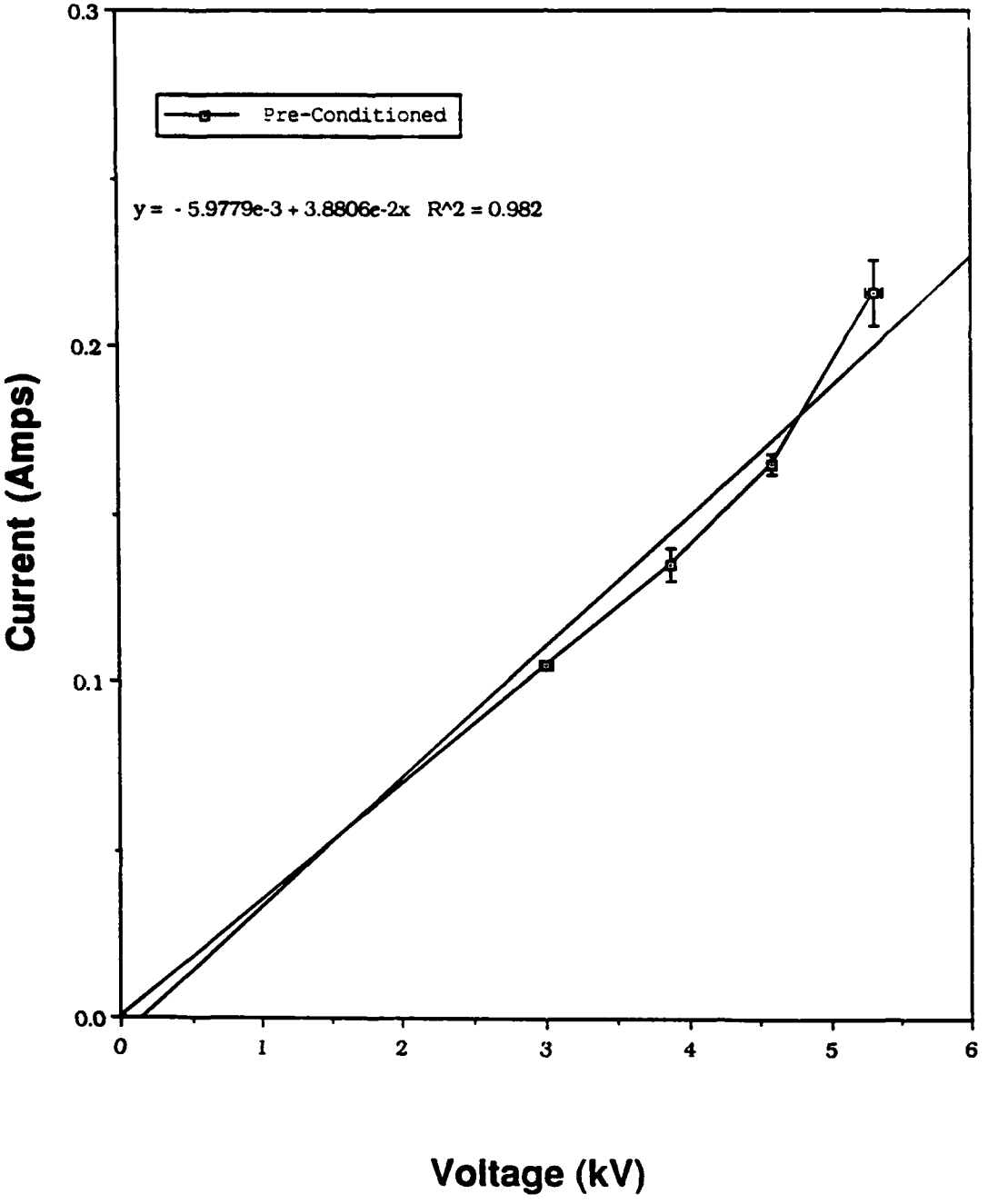

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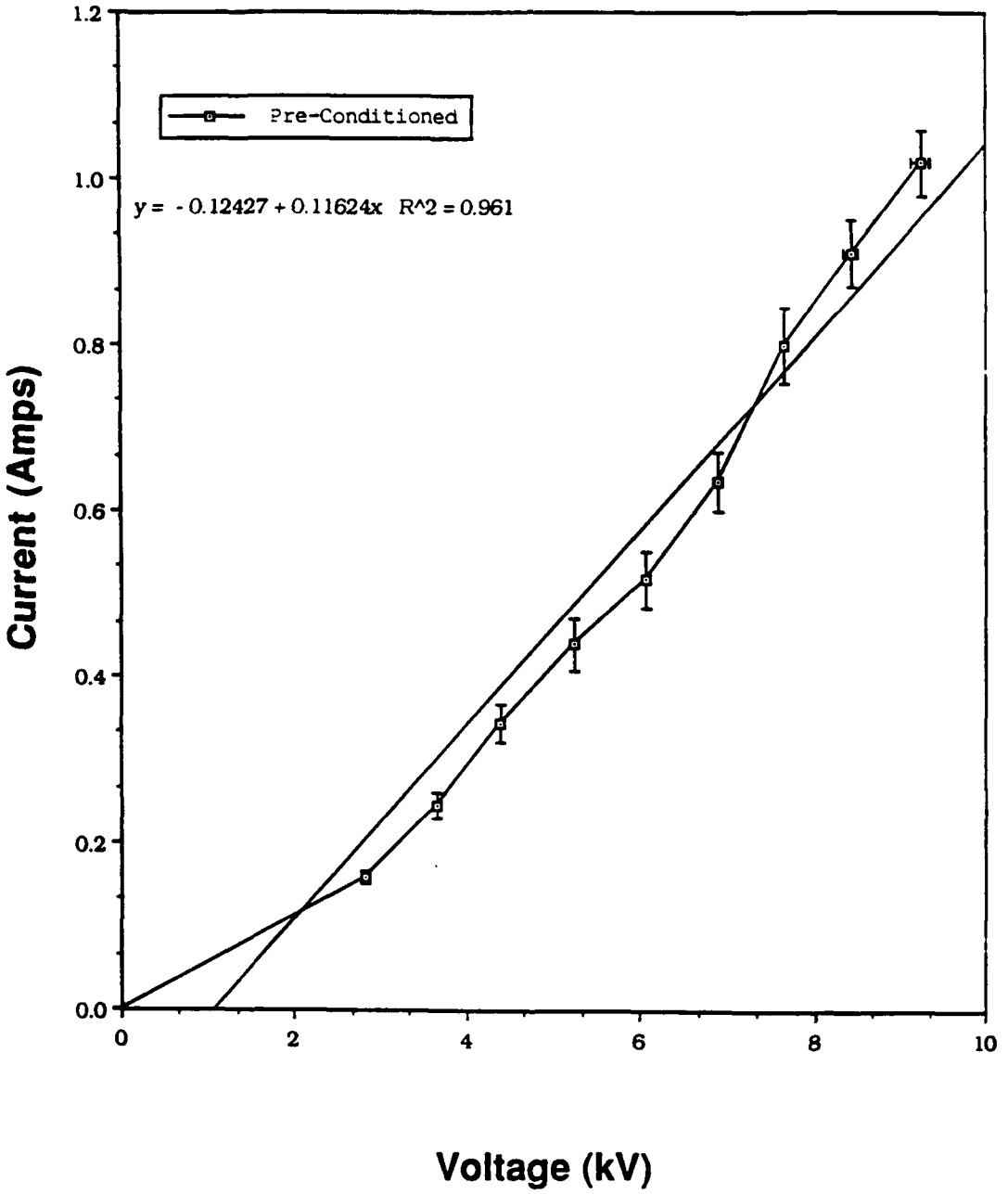

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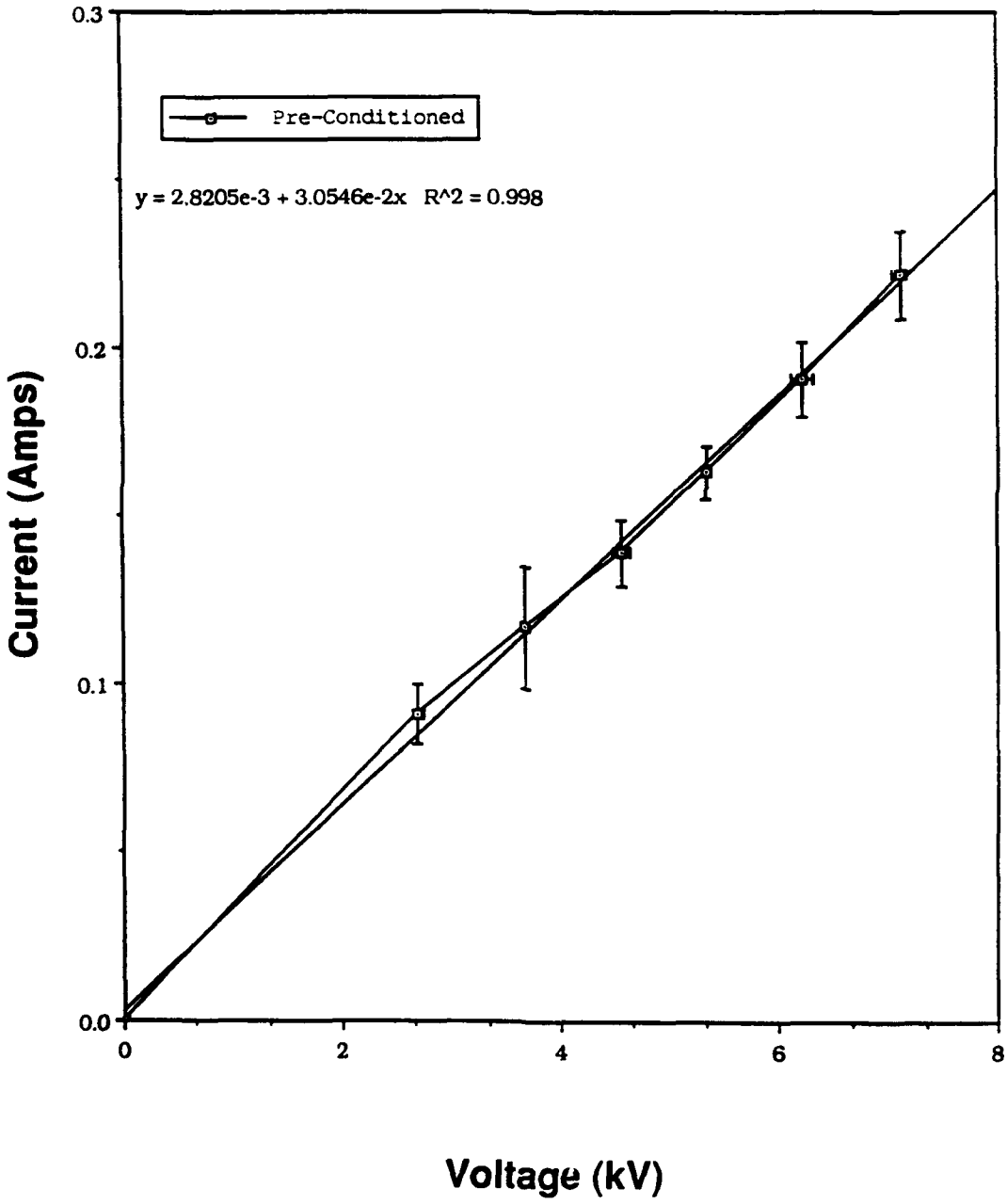
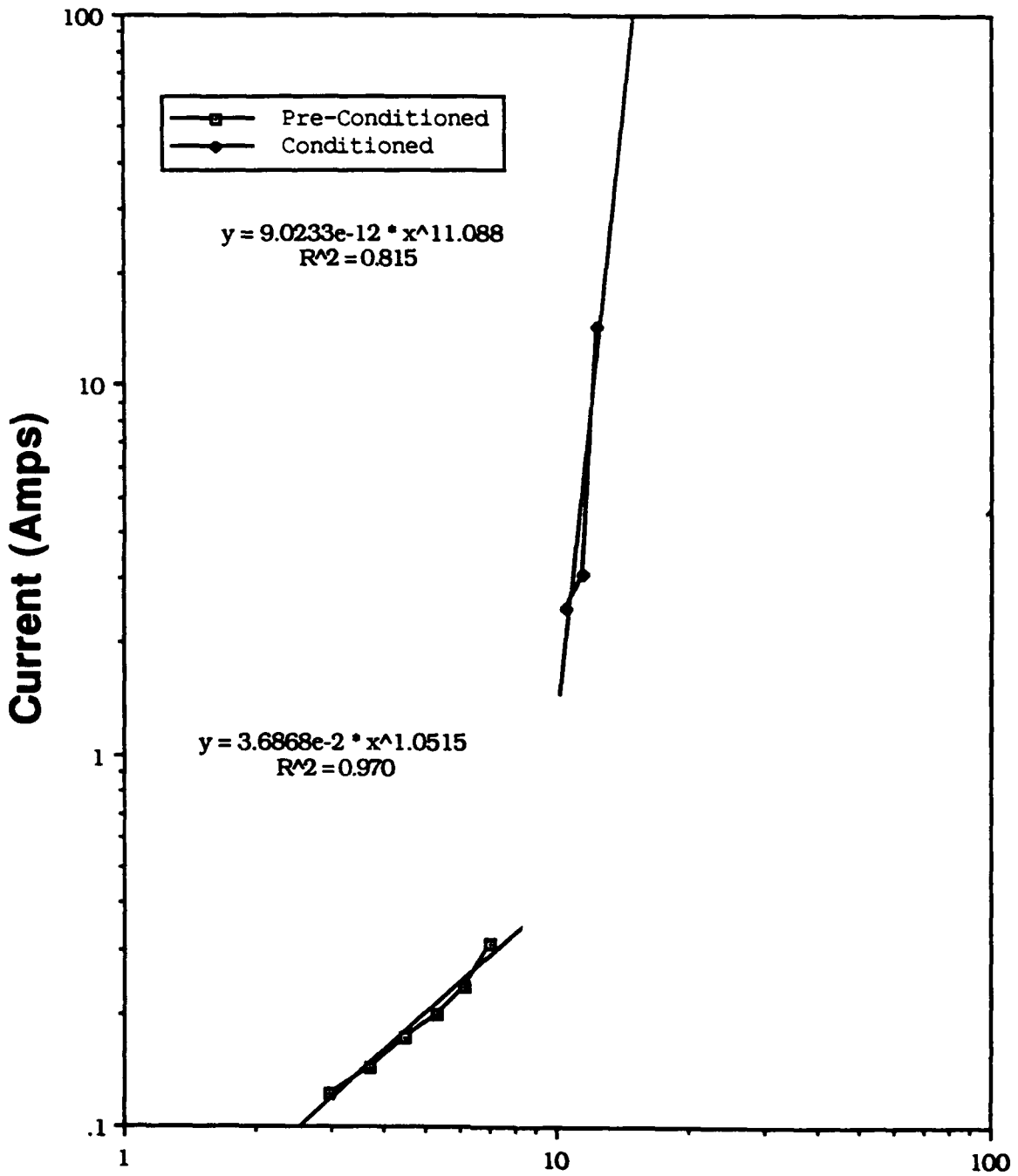


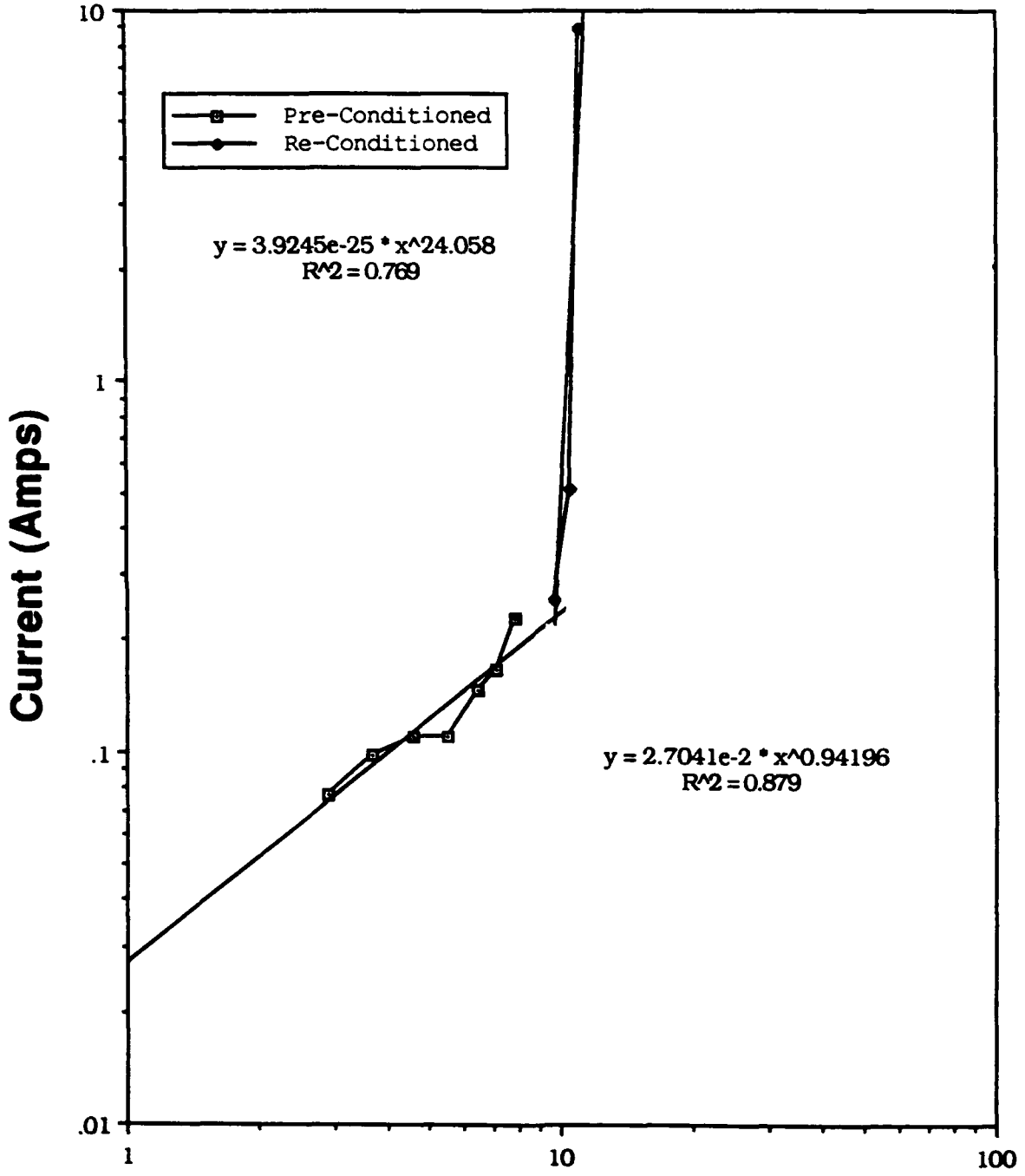
Appendix C

I-V Curves with Power D

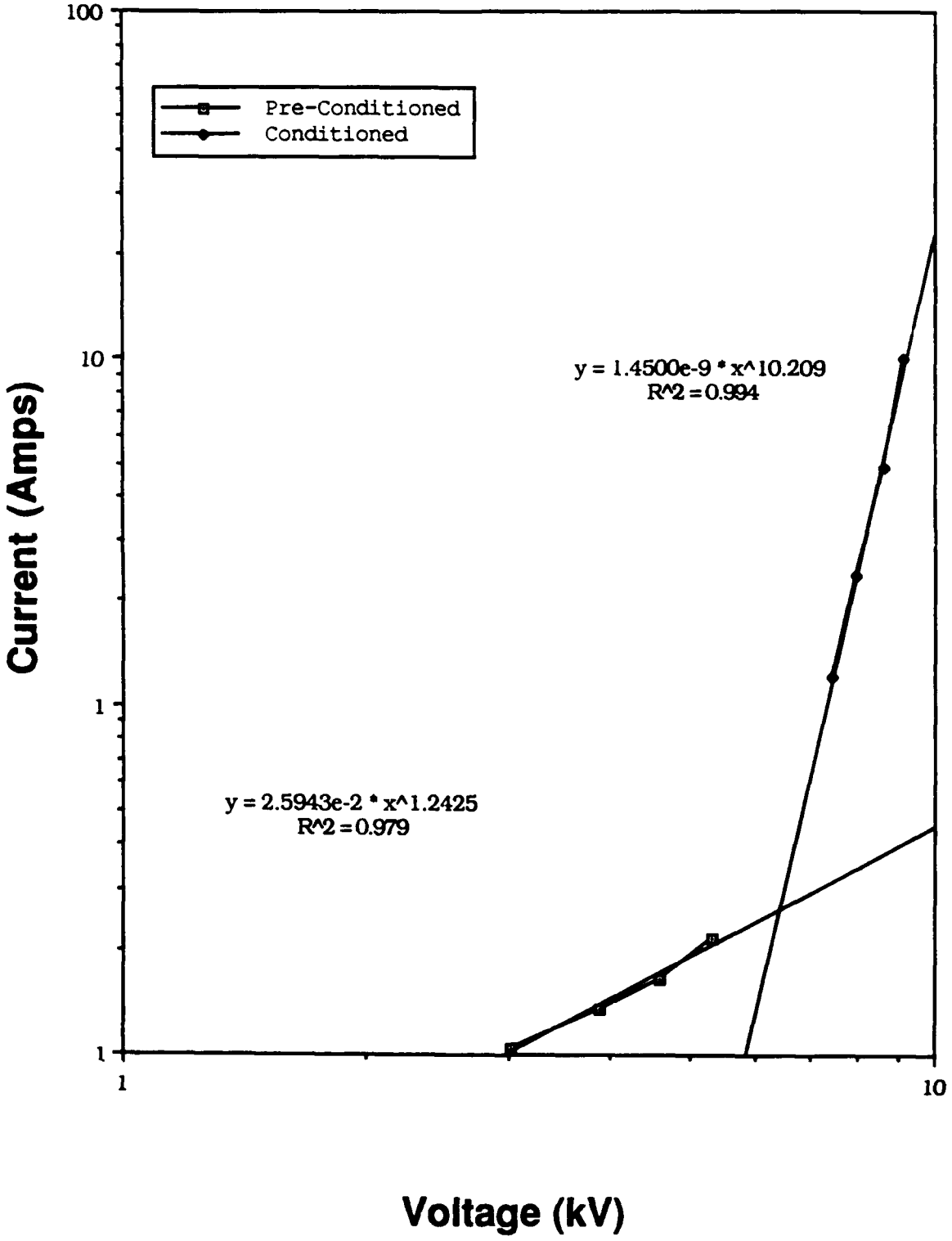
Boron at Cathode



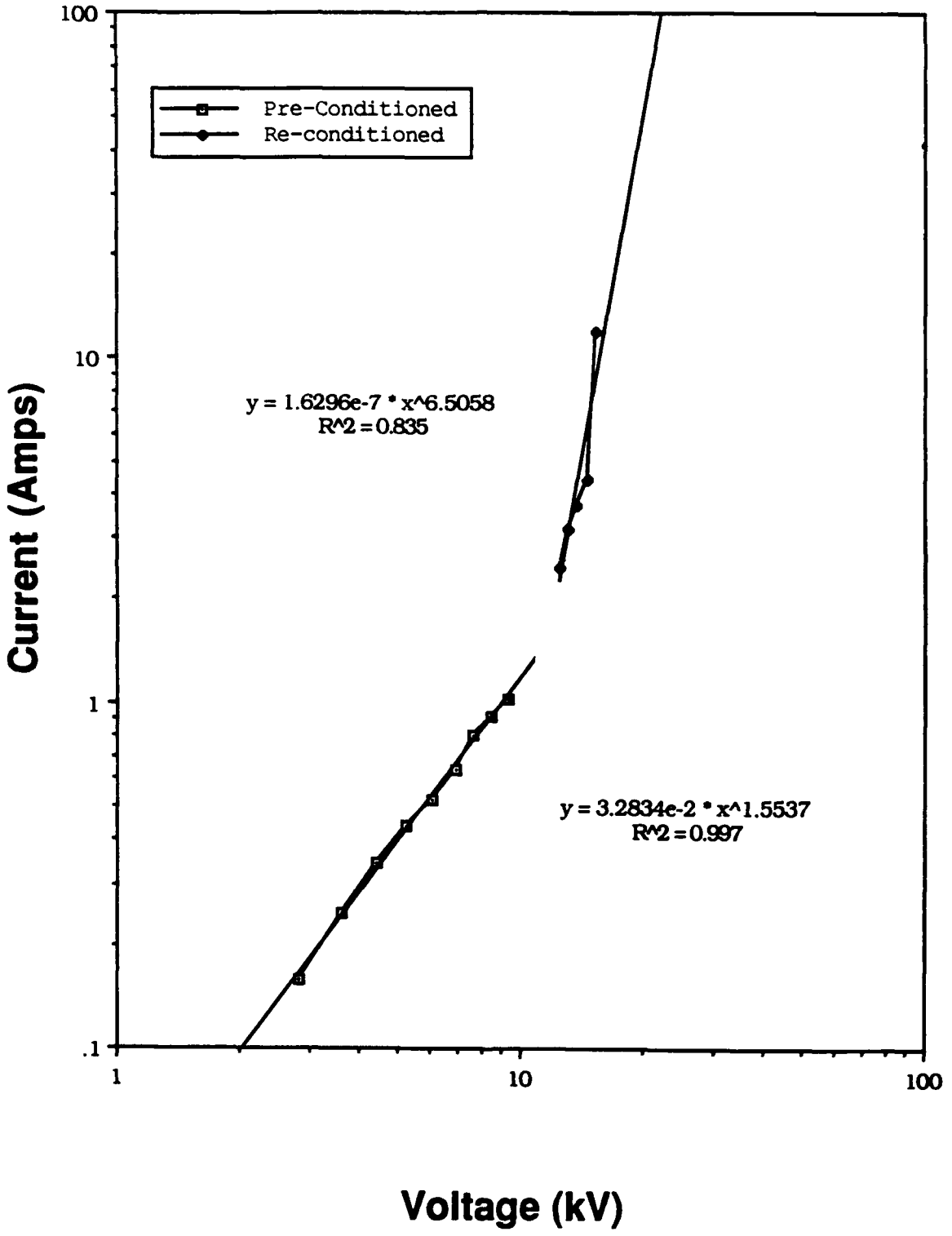
Boron at Anode



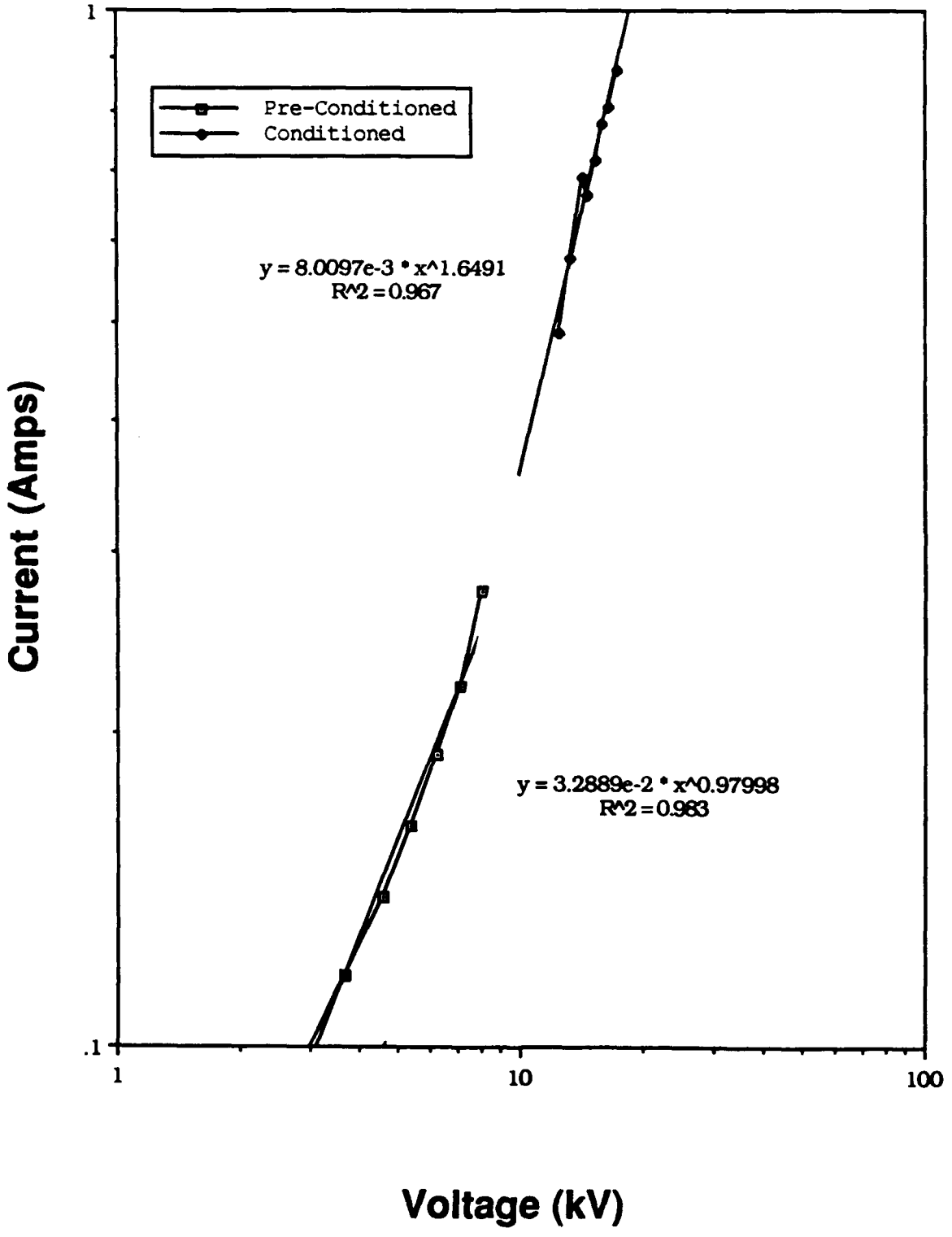
Pure Silicon



Oxide at Cathode



Oxide at Anode



Works Cited

1. Petr, R.A. et al. "Switching performance of a cryogenic photoconductive power switch," J. Appl. Phys. 63, 8 (15 April 1988).

2. Loubriel, G.M. et al. "Surface flashover threshold and switched fields of photoconductive semiconductor switches," IEEE Conference Record of the 1988 Eighteenth Power Modulator Symposium, 1988.

3. Williams, P.F. and Peterkin, F.E. "A mechanism for surface flashover of semiconductors," Digest of Technical Papers, 7th Pulsed Power Conference, Monterey, 1989.

4. Loubriel, G.M., O'Malley, M.W. And Zutavern, F.J. "Toward pulsed power uses for photoconductive semiconductor switches: Closing switches," Digest of Technical Papers, Sixth IEEE Pulsed Power Conference, New York, 1987.

5. "Photoconductive Switching at LLNL," M. Pocha, Workshop on Optically and Electron-Beam Controlled Semiconductor Switches," Norfolk, VA 1988.

6. Peterkin, F.E. and Williams P.F. et al. "Inhibition of surface flashover on silicon due to weak visible or infrared illumination," Appl. Phys. Lett. (Jan 1992).

7. Anderson, R.A. and Brainard, J.P. "Mechanism of pulsed flashover involving electron-stimulated desorption," J. Appl. Phys. 51 (1980).

8. Miller, C.H. "Surface flashover of Insulators," IEEE Transactions on Electrical Insulation, 24 (1989).

9. Williams, P.F. and Peterkin, F.E. et al. "Surface flashover of silicon," Department of Electrical Engineering, University of Nebraska-Lincoln, Private Communication.

10. Garrett, C.G.B. and Brattain, W.H. "Some experiments on, and a theory of, surface breakdown," J. Appl. Phys. 27 3 (1956).

11. Sze, S.M. Semiconductor Devices: Physics and Technology. (John Wiley & Sons 1985).

12. Klein, N. "Breakdown mechanisms of thermally grown silicon dioxide at high electric fields," The Physics and Technology of Amorphous SiO_2. (Plenum 1987).

Vita

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For many applications such as lasers and radar drive circuits, there exists a need for solid state high voltage, high current switches. Current gaseous discharge switches fail to satisfy the ruggedness, reliability, and lifetime requirements of today's systems. A promising alternative is the Photoconductive Semiconductor Switch (PCSS). The limiting factor in the operation of these switches is the occurrence of breakdown through channels formed slightly below the surface. A theory on the formation of these channels is presented based upon band bending at the metal-semiconductor interface, a nonhomogeneous space charge due to irregular trap distributions, and thermal runaway in localized regions. Experimental results on the effect of thin oxide layers and boron doping at the metal-semiconductor interface reveal that the junctions play a very important role in the breakdown of the samples, changing the breakdown potential by almost a factor of three. By placing a thin oxide layer at the anode face of a sample, an excellent photoconductive switch can be produced. The resistance of this switch was changed by three orders of magnitude through optical illumination.

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